GEOLOGIC STRUCTURES

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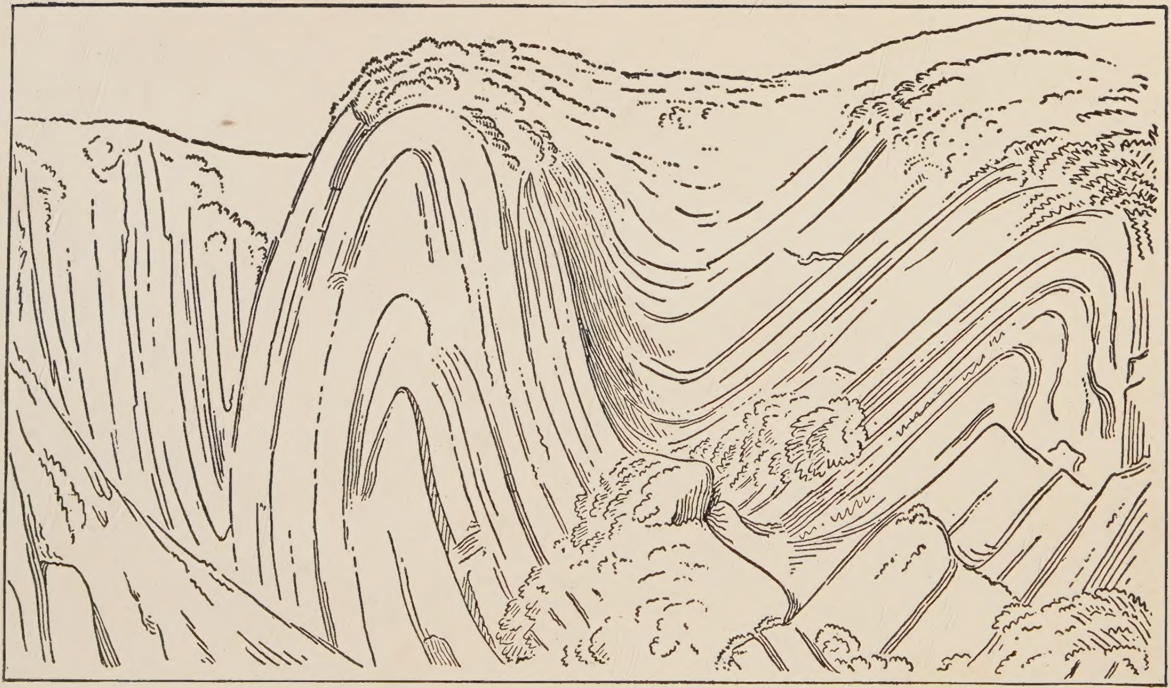

(*Frontispiece*)

Contorted strata on the coast of Berwickshire, Scotland. (After Sir James Hall, Bart. 1812.)

GEOLOGIC STRUCTURES

BY

BAILEY WILLIS

AND

ROBIN WILLIS

SECOND EDITION

REVISED AND ENLARGED

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PREFACE TO THE SECOND EDITION

Six years have elapsed since this book was written and changes have taken place in the estimate of its purpose. A more comprehensive scope is thought appropriate.

Sedimentary processes are given consideration. The action of vertical forces is discussed and warped structures are described. Igneous and metamorphic structures are more fully considered. The chapters dealing with mechanical principles as applied to the analysis of structures have been rewritten. The substance of the original work, thus revised, is included in Sections I and II.

Section III deals with methods of attack and comprises the original chapter on field methods, together with the chapter on graphic methods and practical problems, the latter being added to.

The treatment of the general subject, geologic thought, has been materially amplified by an account of the current theories of the origin of the earth and its dynamical development, taken up in Section IV.

The aim is to make the volume useful to the student and teacher, as well as to the field geologist and engineer having to do with structural geology.

Robin Willis, who contributed to the first draft, has now become co-author with myself. He has given special attention to the revision of Chapters VIII–XII and Chapter XIV. I am entirely responsible for Section IV. We have coöperated in discussion of all chapters, I bringing broader experience and observation, he contributing more precise technical training to check generalizations.

Bailey Willis.

Stanford University,
July, 1929.

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PREFACE TO THE FIRST EDITION

The purpose of this book is to describe geologic structures and to apply the principles of mechanics to their interpretation. The work is in some sense a technical and advanced study, and yet it is possible that the effort which has been made to present the subject simply, in English rather than in Geology, may be successful to the extent of throwing light on the subject for the untechnical reader as well as for the special student.

To G. K. Gilbert, who thirty-eight years ago suggested the study of the mechanical principles underlying structural geology, I owe my introduction to the subject. The "Mechanics of Appalachian Structure" was inspired by him. To the great Swiss geologist, Albert Heim, I, together with many colleagues, owe the recognition of the fact that he laid the corner-stone of our work in "Das Mechanismus der Gebirgsbildung." To C. R. Van Hise and to many colleagues still living I am indebted for more helpful suggestions than I can acknowledge. For the views here advanced, however, in so far as they may present any novelty, I alone am responsible.

BAILEY WILLIS.

SANTIAGO DE CHILE,
May, 1923.

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GEOLOGIC STRUCTURES

INTRODUCTION

OUR CHANGING EARTH

"I have seen mountains built by the Great Spirit" was the answer of an Indian when asked what he thought on first seeing the Capitol at Washington. Men's structures did not impress him. Neither could he have explained what he meant by saying that mountains are built, for he knew nothing of rocks or of their making or of mountain building.

One of the most ancient riddles of Nature is the occurrence of marine shells on dry land, often at great altitudes. The climbers of Mt. Everest found them in the solid rock at a height of twenty-seven thousand feet. The Greeks found them on the slopes of Parnassus. Several explanations have been offered: the shells are special creations, a local detail of the general scheme of creation; or they are evidences of the universal deluge; or the sea formerly covered all lands and mountains before any dry land appeared; or from time to time the sea has spread over the lands and again withdrawn; or the sea bottom has been thrust up by mighty forces to form mountain chains.

The student who can discuss these alternative explanations intelligently, opposing to each one the critical facts by which it can be tested, will know a great part of the contents of this book.

An English engineer, some two hundred years ago, engaged in digging a canal across gently inclined beds of chalk, observed that fossil shells collected from the bottom layers differed from those found in higher layers, while those which were characteristic of the layer at one place were found wherever that layer occurred. His observations have been verified not only for the chalk strata of England and France but also for other successions of stratified rock, of very different ages and in all parts of the world. During some hundreds of millions of years layers of sediment have gathered in one basin or another on the earth's surface, and with occasional exceptions each layer a few feet thick contains fossils peculiar to the epoch at which it was deposited. The total thickness of such strata, if piled up in one place, would be many times the height of the highest mountain. How then can we ever see the bottom layers or the middle ones or any but the uppermost ones? William Smith, digging canals across the uptilted edges of the English chalk, might have answered by pointing to the inclination of the strata; but how they had become inclined was a problem in structural geology that neither he nor anyone else in his day could have answered.

The logical Scot, Sir James Hall, who in 1788 first reasoned that contorted strata, such as he saw in his walks along the coast, must have been wrinkled up by horizontal pressure, took a long step in structural geology. His novel idea that strata had been folded is now one of the well-established commonplaces of the science.

Sir James was logical, not only in reasoning from what he saw but also in explaining the process according to his experience. His experience told him that rock cannot be bent. Since he observed it to be bent the layers could not have been rock but must have been soft mud when the bending occurred. In that conclusion he was mistaken. Three-quarters of a century after him the Swiss geologist, Albert Heim, showed that rocks must have been hard and might have been crystalline as marble when folded.

Heim lived, climbed, and thought among the Alps. Inspired rather than awed by their grandeur, he reasoned in terms of their magnitude. Seeing in the distorted forms of the rocks that the mountains themselves had moved, he realized that their overpowering weight would confine deeply buried rocks and prevent them from breaking, even though folded over and rolled out.

Interpreting his observations of the lay of the disturbed strata by applying the principles of mechanics to the changes of form and position they had suffered, he laid the foundations of engineering structural geology. That was half a century ago.

The folded structures of three mountain ranges had then been studied. They were the Jura of France and Switzerland, the Swiss Alps, and the Appalachian ranges of North America. In their masses are strata which once accumulated on the subsiding sea bottom until they were many thousand feet thick, and which were afterwards pushed into great folds as a heavy cloth may be wrinkled on a table. But in order that a cloth shall so wrinkle it must move over the table beneath it, must shear over the table, as an engineer says. The same is true of folding beds of rock. They must shear over some surface beneath the mountain; they must be thrust forward. Shearing or overthrusting had long been known, but had been classed as a result of folding rather than as an effect which must precede folding on a large scale to supply the length of strata taken up in the folds, as is now realized.

When geologists were faced with the problem of explaining how it is possible that beds of rock 10,000 or 20,000 feet thick should be sheared across and folded up, they generally agreed with old Sir James that the rock must have been relatively soft; only they said "plastic." Heim, they said, was also right. The excessive load that kept the strata from breaking made the rock soft and "plastic." Unfortunately the latter is not true. Forty years ago G. K. Gilbert, a deep thinker, reasoned that excessive pressure must increase internal friction and by rights should increase strength when applied on all sides. At his suggestion Frank D. Adams tested the effect experimentally and proved that rocks are many times stronger when greatly compressed, as they are a few miles below the surface of the earth. Unable to solve the problem by assuming that "plastic" rocks have been disturbed by moderate forces, we are obliged to look for forces intense enough to overcome the rigidity of the strongest rocks.

This is an engineering problem. Masses are squeezed and obliged to change their form. How do they behave? We learn by examining the structures. Why did they behave in that way? We deduce the action from the effect by applying the principles of mechanics. That is the method of structural geology. It leads to an understanding of the development of mountain chains and continents and is an essential foundation for all other branches of geology, whether in research or in application to mining and engineering constructions.

Evolution rests for proof on structural geology. A row of fossils demonstrates evolution, provided they are placed in their natural sequence of occurrence according to the relative ages of the strata in which they are found. We can so arrange them, from the ancestors of the trilobite to man; but suppose that the order is challenged, as it has been by a fundamentalist who, more sincere than informed, masquerades as a geologist? The fossils have been collected in many parts of the world from successive strata, laid down one stratum upon another, the younger on the older. The older contain certain fossils, the younger contain different ones. We trace relationships, lines of descent; hence evolution. But suppose that somewhere the strata are upside down? In exceptional cases they are overturned and it is not always obvious whether this is so or not. Only through application of the principles of structural geology can we determine which strata are older, which are younger, and what has been the real course of evolution.

In mining, a knowledge of structural geology is a prerequisite to intelligent planning of the mine. Ores are usually chemical concentrations in rock masses. They concentrate where there is a space. Spaces develop underground as a result of jointing or faulting, sometimes, it is true, without order, as in quicksilver mines in serpentine, but far more often according to a system. The mining engineer who knows how to recognize and interpret that system, whatever the effect of elongation and compression may be, is worth his cost at any price. He will avoid expensive mistakes; he may find the ore.

Back in the eighteen seventies a mine in the Rocky Mountains which had paid large profits was sold. The price was proportionate to the promise, but the promise was not fulfilled. The buyers very soon lost the ore on a fault. Their engineers, backed by the ablest geologists of the day, called it a normal fault and prospected for the vein according to the rules that apply to normal faulting, but they found nothing. The buyers sued the sellers. It was a celebrated, if not notorious case. But not till fifty years later was the ore found, when a youngster from college, instructed to recognize a thrust fault when he saw it, worked out the displacement correctly and directed a deep drill into the lost millions.

King, Emmons and Hague were excusable. They knew all there was to know in their day. It is otherwise now. We know a great deal more about the mechanics of rock structure. We need to, for the rich bonanzas are worked out, poorer ores must be mined at greater depths, and the cost of misinterpretation must be eliminated by trained understanding.

Petroleum geology demands even more thorough training and wider knowledge than mining. I. C. White first identified the occurrence of oil with the trend of an anticlinal axis in West Virginia and made a fortune out of his confidence in the relation. Thousands of successful wells have since been located by that clue, but many others have failed. They missed the top of the fold, or the structure was not " closed," or it was faulted, or—well, there was some peculiarity of the structure that was responsible for the failure. Perhaps the geologist who located the well could have known it, perhaps he could not, but certainly the more geology he knows and the more intimately he knows anticlines, faults, echelon folds, and many other types of structure on which oil may accumulate, the better his chance of striking it.

The needs of crowding populations for water and the demand for hydro-electric power are reacting upon the work of geologists. Dams and aqueducts must be constructed on a scale never before attempted. Sad experience from time to time demonstrates the weakness of foundations and proves that natural rock may be less firm than artificial concrete. Water under pressure is a sly and patient giant, searching out every crevice, every pore, and lifting. The geologist, upon whose reputation a dam may be built, must pit his knowledge of rocks against the giant and outwit him. It is not often easy.

A new profession is developing. We have long had geologists and also engineers. We now have the geological engineer. An engineer, competent in mechanics, experienced in construction, able in hydraulics, he also possesses a knowledge of structural geology, knows how rocks behave when deformed in the course of mountain building, and can interpret folds, joints, and faults understandingly.

Thus in practice as well as in research structural geology is an essential feature of the preparation of a man who seeks to advance in the profession of a geologist.

SECTION I

DESCRIPTIONS OF ROCK STRUCTURES

It is the intention of this section to describe the forms which masses of rock may present. Every rock tells a story. The beginning of the story is to be read in the kind of rock and its original structure. The continuation is to be found in the changes of original character or form. To be able to recognize and interpret these facts is to know the A B C of structural geology.

CHAPTER I

STRATIFIED ROCKS

Sedimentary strata described; their lithologic variations illustrated; the geographical conditions of their origins suggested; their grouping considered; and their changes of form and constitution as they lie in the place of their formation sketched. The subjects presented in this introductory chapter will be found more fully treated in the works on sedimentation listed.

STRATIFICATION

Definition.—*Stratification* is that original structure which divides sediments into beds, layers, or strata. The structural unit of stratified rocks is a *bed*, a *layer*, or a *stratum*. It has great extent in all directions in one plane, but perpendicular to that plane it has very slight thickness. The extent is measurable in miles, the thickness only in feet, inches, or fractions of inches.

In common usage the term bed or stratum is applied to a division which has a thickness of a few inches or feet. Layer is used to describe thinner divisions. *Laminæ* are layers of the thickness of paper.

Stratification is the result of interruptions in the process of accumulation of sediment. It is therefore a character imposed upon the sediment as it accumulated, and is an original inherent characteristic.

Bedding is a term of broader application than stratification, since it is not limited to sediments, but is used as pertinently to describe the structure of igneous or metamorphic rocks, such as tuffs, lavas, granites, gneisses, or schists, when these rocks occur in layers of greater or less thickness. Bedding may be due to any one or to several of a number of diverse conditions, to be described in their appropriate context.

Neither stratification nor bedding can be used properly in connection with the effects of mechanical pressure, to which the terms jointing, cleavage, or fissility apply. Nor is the development of shelly layers in consequence of chemical alteration a form of stratification.

The Origin of Stratification.—Sediments are distributed by currents of air and water, and are deposited over wide areas in relatively thin masses. They thus form strata, the structural unit of stratified rocks. Strata then owe their existence to deposition, and as long as deposition is continuous the result is a stratum. But when deposition is interrupted that stratum is finished, and another may be spread over the first only when deposition is renewed. It is thus evident that stratification originates in discontinuous or interrupted settling of sediments from currents of air or water.

The upper surface of any one stratum is in contact with the lower surface of the succeeding stratum along a plane which is called a bedding plane. It is a flat or gently curved surface which, in its original attitude, may be nearly or quite horizontal, but may also, under certain conditions of deposition, as on the face of an embankment, be formed in an inclined position. We shall see later that strata may be warped or bent and thus may assume inclined positions quite different from their original attitude.

Varieties of Stratification.—Stratification may be obscure or distinct. For instance, if the sediment be coarse sand, the surface of the deposit is rough, and even though sedimentation be interrupted a later deposit of similar sand interlocks with that previously laid down, leaving only an obscure bedding plane. There is a tendency to massiveness in sandstones, and when that is not the case any evident bedding is commonly due to alternations of strata of sand with thin layers of clay.

Stratification in shale is often not obvious to the eye, the material being homogeneous, but it is mechanically well defined. Interruptions are apt to be frequent during the deposition of mud, and the surface of the deposit may harden or may be scoured by currents capable of removing loose material. There is then an absence of bond between the earlier and later accumulations, and their plane of contact becomes a plane of splitting. Shales are characteristically thin-bedded and split readily on the bedding planes. Weathering often brings out the tendency to split or accentuates differences of color, but chemical alteration may result in deceptive similar appearances which actually lie at angles to the original stratification.

Limestones accumulate as calcareous muds in depths which are often below the reach of superficial currents. They are, therefore, less liable to interruption of deposition than muds and sands accumulating in shallower water. Pure limestones are, therefore, relatively thick-bedded. Limestone deposits do, nevertheless, suffer interruption and scour in shallow seas, and they then exhibit well-defined stratification. Earthy limestones are frequently interbedded with shale, and the individual strata may alternate with each other in thin and oft-repeated layers.

Stratification is most obvious where strata differ in grain, color, or composition. Alternations of finer and coarser sands, of sand and shale, or of limestone and shale are of common occurrence, the individual strata being but a few inches or a few feet thick, although their aggregate may attain many hundred feet in thickness. Inasmuch as the change in character is due to a more or less complete change in sediment, each bedding plane is a surface on which the bond is weak. Stratification of this kind is, therefore, not only obvious but mechanically well defined. The strata separate readily on the bedding plane, and if subjected to appropriate forces they will slip past one another on the bed. Such masses are therefore flexible.

Dimensions of Strata.—Any stratum is a lens. It is commonly a lens of very large diameters as compared with its thickness, and this disproportion in dimensions has an important bearing on the resistance which it offers when it is subjected to pressure in earth movements. The dimensions of strata affect their rigidity or flexibility and determine their manner of yielding. The size of

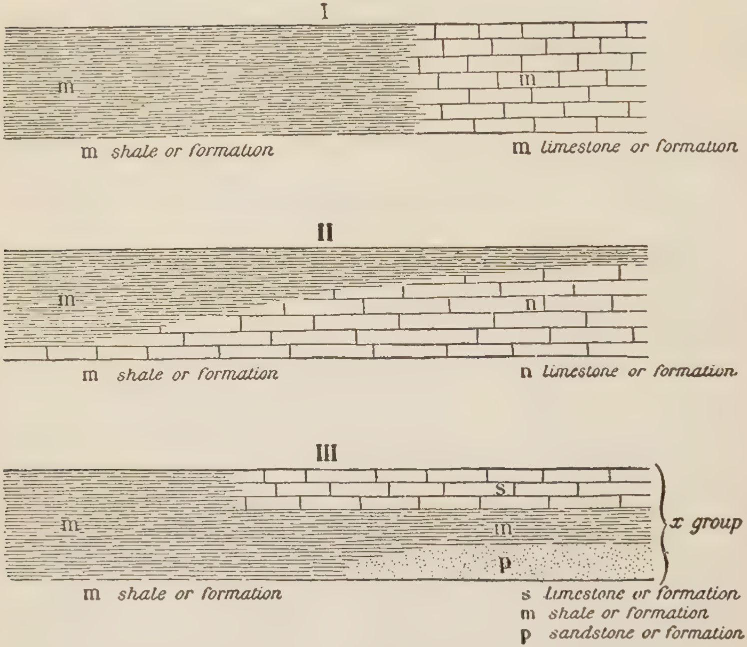
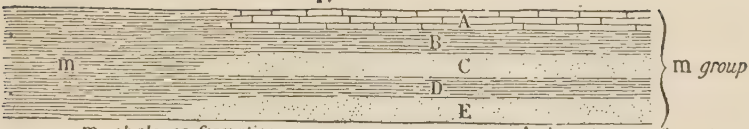


Fig. 1.—Lithologic Units. Part I shows the *m* shale passing into a limestone which retains identical stratigraphic associations. Being exactly continuous stratigraphic units, they should retain the same geographic name on grounds of convenience and simplicity.

Part II shows the *m* shale grading into a limestone with prolonged overlap, so that the two rocks must be discriminated in one area. Not only are they lithologically different but they have different stratigraphic associations, and they should receive distinct geographic names; *m* shale and *n* limestone.

Part III shows the *m* shale continuing as an individual with reduced thickness into new stratigraphic associations. Individuality is not dependent on thickness nor on stratigraphic association only; it is determined by continuity, and the formation may retain its name, *m* shale. But the group *pms* cannot then be called the *m* group, because *m* would have two meanings, one for a simple part, and one for a complex whole.

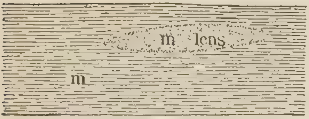
IV



m *shale or formation*

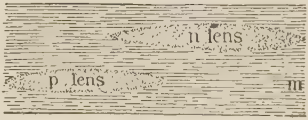
A *limestone or formation*
B *shale or formation*
C *sandstone or formation*
D *shale or formation*
E *sandstone or formation*

V



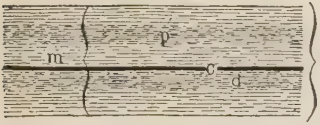
m *shale or formation and* m *lense*

VI



m *shale with* n *and* p *sandstone lenses*

VII



m *shale or formation including* p *fire clay member* c *coal member, and* d *fire clay member*

Part IV shows the *m* shale replaced by five formations, two of which, *B* and *D*, are shales like it. Individuality is here lost in multiplicity. Neither *B* nor *D* can be distinguished as representing *m*, which must, accordingly, give way where they divide into two. The complex *ABCDE* may be called the *m* group, since it has equivalent stratigraphic associations with *m*.

Parts V and VI illustrate the occurrence and naming of local lenses in a formation where such divisions are not of sufficient extent to justify a distinct series of names for the lens and the parts of the formation above and below it. One lens may receive the formation name, but two or more must be named distinctly.

Part VII presents the case of a formation which is the least practicable lithologic individual for mapping, but which includes fractional parts that are important in discussion. The fractional character of the parts may be indicated by calling them members, each member being given a distinctive geographic name.

lenses is important from another point of view, for porous strata are the reservoirs in which water, oil, and gas gather.

To obtain some idea of the dimensions attained by strata we may glance at some of the original structures which are built up by their accumulation. The alluvial cone is formed of innumerable lenses of coarser and finer conglomerate, sands, and clays, distributed irregularly throughout the mass. No single stratum extends far. The diameters are a few hundred or a few thousand feet, and the thicknesses a few inches to a score of feet. In desert basins the slopes which extend from the base of the mountains consist of alluvial fans that often merge into one another and possess similar internal structures in their upper portions, but further out from the ranges become more uniform in texture and consist of more extensive lenses. The alluvium of a great river like the Mississippi is very widespread, but within narrow limits is also very variable. The strata of fine sand and clay, which are distributed by winds or floods over an intermontane basin like that of Great Salt Lake, or the lacustrine deposits of large lakes are among the most widespread and uniform of continental formations.

Beach and along-shore deposits are commonly long and narrow, after the pattern of coastal features. Exceptions to this rule are found in extensive sediments which represent migrating conditions, such, for instance, as the Trinity sands that mark an advance of the waters of the Gulf of Mexico over eastern Texas and Oklahoma.

The fine, muddy sediments of those shallow seas, beneath which practically all of the continents have at one time or another been submerged, are the most uniform, the most extensive stratified deposits open to our observation. The physical and biological history of the continents is there chiefly recorded. In these widespread strata of bygone ages we may also trace the structures which have resulted from mountain growths, and study the mechanics of earth movements.

Thin strata of even greater extent, covering many thousands of square miles, lie beneath the oceans, but they are nowhere revealed to view.

Consolidation of Sediments.—Consolidation of mechanical sediments is an important part of the process of forming strata. The effective force is gravity, which acts to press the particles closer together and to bring them into contact. The interstitial air or water is pressed out in proportion to the effect of compacting. It is clear that the possible effect of consolidation in reducing volume must depend on the proportion of pore space to grain space, and also, since the consolidation is an effect of settling under weight, it will result in a proportionate decrease in thickness of strata.

Assuming the least compact state of solid strata to be that in which the grains touch one another, it has been shown theoretically by Slichter that the pore space in sands of uniform spherical grain may range from 47.64 per cent down to 25.95 per cent, according to the arrangement of the grains.[1] If the grains be angular the pore space may be even greater in proportion to the whole, but where the grains are of mixed sizes it may be less than the minimum for spherical grains. Wind laid sediments are apt to be looser and more uniform in size than water laid sediments, and the effect of compacting under load is then greater. In any case, however, an effect of vertical pressure due to loading must be to reduce the thickness of strata by consolidation by a notable amount. According to the range indicated by Slichter, the reduction in thickness may readily be as much as one-fifth.[2]

Since the thinning of the stratum by consolidation is a considerable fraction of the vertical thickness, it follows that the absolute amount of thinning will be greater for thick beds or in the thicker part of a variable bed. The subsidence of the upper surface of any stratum or of a group of strata will vary accordingly, and so also the departure of that surface from the original, nearly flat conditions. Thus, the settling of the materials may be one cause for the development of gentle flexures in a series of strata.

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[1] SLICHTER, C. S., Theoretical Investigation of the Motion of Ground Water. U. S. Geol. Surv., *Ann. Report* XIX, Pt. II, pp. 306–317, 1899.

[2] For observations of the pore space of many sands, soils, and artificial substances, see KING, F. H., Principles and Conditions of Movements of Ground Water. U. S. Geol. Surv., *Ann. Report* XIX, pp. 209–216, 1899.

Consolidation also increases the strength of stata in an important degree. As is pointed out by Van Hise, strength depends upon the number of points in contact, and consolidation increases that number, as well as the bonds of adhesion and cohesion among the grains of sediment.[1]

Cementation, the process of cementing sediments by deposition of substances brought in solution, strengthens rock by knitting the particles together in a matrix. Lime, silica, and iron oxide are the more common cements. The effect depends upon the percolation of solutions and is therefore common in strata of large grain and large pores, such as sandstones, whereas it is practically lacking in fine-grained rocks like shales. Strata are thereby rendered less flexible, more rigid, and therefore more competent to resist when subject to pressure in the direction of the bedding.

Limestone, in view of the ease with which calcite recrystallizes, is self-cementing and is among the strongest of sedimentary rocks. It therefore forms the controlling competent strata in a series in which it is interbedded with sandstones and shales and which transmits pressure in the direction of the bedding.[2]

WARPING

General Statement.—We assume that the earth's surface is constantly being very gradually warped up or down. To test this assumption we may reason out the result of erosion on an absolutely rigid earth. Start with mountains that are not to grow as they waste away and with hollows that are not to deepen as they fill up. Put erosion to work. Compare the results with the actual heights of continents and depths of basins or with the thicknesses of sediments which have accumulated during past ages.

If the hypothesis of an absolutely rigid earth does not work the student may consider the alternative hypothesis of a warping surface, which means that some areas of the earth's surface rise while others subside. We can make the hypothesis natural by making it flexible. That is to say, the rate of warping up or down may be assumed to be faster or slower than the rate of erosion or of deposition of sediment. Very suggestive results follow.

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[1] Van Hise, C. R., Treatise on Metamorphorism. U. S. Geol. Surv., *Mon.* XLVII, p. 596, 1904.

[2] Adams, F. D., On the Amount of Internal Friction Developed in Rocks during Deformation, and on the Relative Plasticity of Different Types of Rocks. *Jour. Geol.*, Vol. XXV, pp. 626–627, 1917.

Effects of Warping.—Warped surfaces are usually broad and of moderate slopes. Thus, Hudson Bay, the Mississippian embayment, and the valley of California are typical broad downwarps. The Laurentian shield is an upwarp. The dome-like elevation of the Appalachian mountains[1] is an upwarp that has grown since the middle Tertiary and, including the zone of Paleozoic folding, extends far beyond it. The Great Plains are warped and tilted. The high plateaus of Colorado and Utah have been raised by warping.

Downwarps of past ages are usually represented by the strata that accumulated in them. The Palezoic trough of the Appalachian province, the Cretaceous trough of the Rocky Mountain region, the Mesozoic and early Tertiary trough that reached from the Alps to the Himalayas, were all great downwarps. Their bottoms subsided many thousands of feet and the depressions were filled with strata of corresponding thickness, which are now narrowly compressed, folded, and elevated to form mountain chains. Great downwarps of this kind are called *geosynclines*.

Smaller local upwarps and downwarps are of very general occurrence. The upwarps are recognized by rejuvenation of streams and other evidences of accelerated erosion, whereas the downwarps are basins in which sediments accumulate.

Warped Strata, Flexures.—Since the strata are usually laid down in basins that are continually deepening, the bottom layers of a deposit must themselves have subsided and been warped. They will have been tilted or have become basin-shaped or trough-shaped, although the uppermost strata may be nearly flat. The strata of any series are therefore not strictly parallel.

In general usage the broad departures of strata from a flat attitude are called folds, as are also the more pronounced bends. There is a difference, however, between the two kinds of forms. The broad type that is produced during the accumulation of sediments or as a result of subsequent warping is due to vertical movements, to subsidences, or to uplifts. The more pronounced bends, such as commonly occur as alternating troughs and arches, are caused by horizontal compression. When both kinds are designated by the same name a confusion of ideas results and may lead to wrong inferences. It is better to call the effects of warping *flexures* and to restrict the terms *folding* and *folds* to the mechanical disturbances caused by compression.

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[1] Hayes, C. W., and Campbell, M. R., Geomorphology of the Appalachians. *National Geographic Magazine*, Vol. 6, pp. 63-126, 1894.

GROUPS OF STRATA

Significance.—Any single stratum is rarely more than a few inches or a few feet thick and therefore has less significance in a series than a page of this book has in the volume. But successive strata group themselves according to some common characteristic, and as a group they represent the conditions of their origin or an appreciable interval of geologic time.

The first task of a geologist in an unfamiliar region is to ascertain what groups of strata are present and what they represent. Color, lithology, a rhythm of similar successive beds, fossils, and other characteristics of each group, are noted and the group is identified by them wherever it may be found. Each group is a structural unit, a building stone of the plateaus or mountains. The contact planes between groups become important features of the architecture; they may be of several kinds, as enumerated below.

Conformable Contacts.—The name means that the two strata which are in contact are parallel each with the other, as are the leaves of this book.

In the usual case the time which has elapsed after a lower stratum was laid down and before the next upper one covered it is brief, the space between tides or storms or floods; but that is not always so. A very much longer interval may be indicated by the absence of strata which elsewhere occur between the two, or by special scouring or erosion of the older beds, or by an abrupt change in fossils from the older to the younger.

A conformable contact between strata which are not separated by a notable time break is called a *diastem.* A conformable contact which is characterized by a notable lapse of time is called a *disconformity.* Diastems are usually not important elements of structure. A disconformity may separate two distinct groups of strata and thus be structurally significant, as it always is stratigraphically.

Uncomformable Contacts.—Place this book flatly across the edges of several others. Its leaves will then have an unconformable relation to the leaves of other books.

Where strata lie unconformably upon an older series the latter has at least been tilted or eroded before the former was spread over its bassett edges. The difference of inclination between the older and the younger strata, which are thus unconformable, may range from a very small angle to 90 degrees. It varies, of course, with the attitude of the older strata when the younger were laid down upon them, and will therefore change from place to place. The size of this angle is therefore not a measure of the importance of the unconformity, though it is often so considered.

An unconformable contact at which there is an angular difference of inclination between an older series and a younger stratum is called a *non-conformity.*

A non-conformity is a structural fact of the first order. It may indicate a large time break and usually divides one group or type of structures from a different type. Thus, a horizontal or gently inclined series of undisturbed strata may rest upon the eroded edges of more or less closely folded strata; or undisturbed beds may lie upon metamorphosed rocks that have been intruded by granite and recrystallized.

Overlap.—If land and sea had stood constantly at the same relative elevation the area covered by water-laid sediments would have remained unchanged. But the relative elevations of land and sea have constantly varied, in consequence of warping, and the extent of sediments has changed from time to time accordingly.

When the level of sea and land has changed as if by subsidence of the land the area of sediments has spread inland. This is called a *transgressive overlap* or *transgression.* At the base of the spreading sediment an overlap produces a contact which advances from a diastem to a disconformity and possibly to a marked non-conformity.

When the level of land and sea has changed as if by elevation of the land the area of sediments is narrowed and sediments recently laid down are washed back into the sea. This is a *regressive overlap* or *regression.* It is not marked, even by a disconformity, as the strata, so far as they extend, continue to accumulate in conformable sequence.[1]

There are many ways in which the relative level of land and sea may change. If the sea level itself be raised or lowered all still-standing coasts will be affected in the same manner. If, on the contrary, sea level remains constant, as for considerable periods it may usually be assumed to be, while the land moves, the effect will vary along any coast according to the topography of the coast and the kind of movement. The land may rise or sink evenly, or may warp and tilt, or may divide into blocks which move, some up, some down. The student who has a grasp of the principles of sedimentation [2] will profit by constructing sections to illustrate the effects of different movements on diverse coasts.

Continental Sediments.—Emphasis is commonly laid upon marine sediments because they form a larger part of the succession of sedimentary rocks than do the continental deposits. The latter occur, however, and they represent special relations of conformity, disconformity, nonconformity, overlap, and regression, which are to be interpreted in terms of subaerial processes in lieu of subaqueous conditions.[1] As a rule the distinction between marine and continental deposits does not enter significantly into the problems of structural geology.

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[1] Grabau, A. W., "Principles of Stratigraphy," pp. 723–745, 1913.

[2] Twenhofel, W. H., "A Treatise on Sedimentation." 1926.

Johnson, D. W., "Shore Processes and Shore Line Development." 1919.

Gilbert, G. K., Topographic Features of Lake Shores. U. S. Geol. Surv., *Ann. Report*, 5, pp. 69–123, 1885.

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[1] WALTHER, JOHANNES., Die Denudation in der Wueste und ihre geologische Bedeutung. *Abhandl.* d. Mathematisch-physischen Classe der Koenigl. Saechsischen Gesellschaft der Wissenschaften, XVI Band, No. III, 1891.

TOLMAN, C. F., Jr., The Geology of the Vicinity of the Tumamoc Hills. Car. In. of Wash. *Pub.* 113, pp. 67–82.

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SALISBURY, R. D., " Manual of Physiography," 1919.

CHAPTER II

FLEXURES AND FOLDS

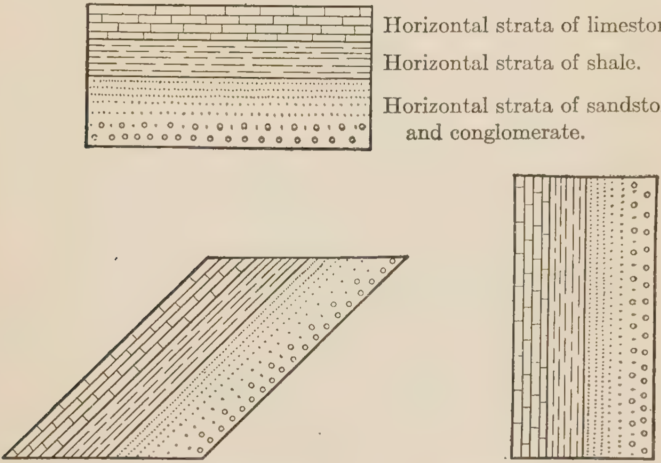
Describes the changes of attitude and form which are observed in stratified rocks in consequence of tilting or warping by vertical forces or of folding by compression.

Attitudes of Strata.—Any stratum is defined by the bedding planes which limit it, and its position in the ground or attitude is fixed by the relation of a bedding plane to a horizontal plane. Thus, if the bedding planes of a group of strata extend in all directions practically horizontally, the attitude of the strata is horizontal. If the planes are inclined to the horizontal the strata are inclined. The inclination may range from nearly horizontal to vertical, and strata may even be pushed over beyond the vertical so that they lie in an overturned position.

Strata which were originally laid down flat, or nearly so, and which extended parallel with one another under the sea bottom or under wide plains, assume an inclined attitude as they subside into the earth or as they are lifted in plateaus and mountains. They then appear as parts of large geologic structures. Their once orderly relations of parallelism with one another are disturbed. Their new relations suggest how they have been disturbed. It is, therefore, the task of the geologist to ascertain both sets of relations, the original order in which the strata were formed and the disturbed arrangement in which they lie.

To describe these relations the geologist employs certain arbitrary references, particularly what are called *strike* and *dip*.

If a stratum be inclined, the largest angle of inclination between the bedding plane and the horizontal plane gives the measure of the inclination. It is called the *dip angle* or the *dip.* If we assume a horizontal plane, $ABCD$, which cuts a bedding plane, $WXYZ$, the acute angle between the planes, measured in a plane vertical to their common trace, is the dip angle (Fig. 3). Let it be noted that the dip angle must be measured in a plane at right angles to the trace, MN. That is the largest of all the angles which might be measured between the bedding plane and the horizontal.


Horizontal strata of limestone.
Horizontal strata of shale.
Horizontal strata of sandstone and conglomerate.

Inclined strata of limestone, shale and sandstone.

Vertical strata of limestone, shale and sandstone.

FIG. 2.—Diagrams illustrating the positions of horizontal, inclined, and vertical strata.

The trace MN of the horizontal plane with the bedding plane is a datum line by which the direction of the extension of the stratum may be defined; for if one follows MN one must follow the surface of the stratum in which MN lies. MN is a horizontal line; any horizontal line makes an angle with the north-south meridian and this angle is the *bearing* of the line. When the horizontal line lies in the surface of the stratum, as MN does, it gives the bearing of the stratum, and this bearing is called the *strike.*

From the preceding we deduce the definitions of strike and dip as applied to strata:

(*a*) The *strike* of a stratum is the bearing of a horizontal trace on the bedding plane.

(*b*) The *dip* of a stratum is the angle between a bedding plane and the horizontal, measured in a plane at right angles to the strike.

It is evident that a horizontal stratum strikes in all directions. A vertical stratum has a dip of 90 degrees. Strike and dip, being angles, are expressed in degrees. Strike is commonly stated as so many degrees east or west of north, thus: strike N. 30 E. The amount of dip is given by its angle, as for instance, 50 degrees, but there are always two planes which may dip at a given angle from any given strike. Thus, if the strike be northeast the dip may be northwest or southeast. Therefore the direction of dip also must be stated.

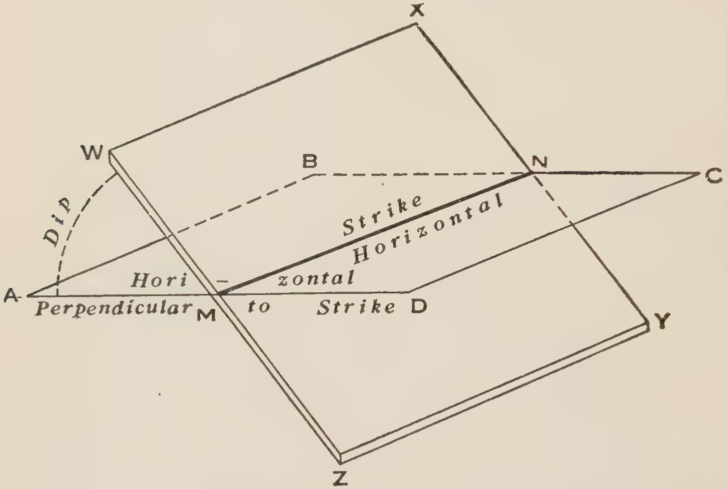


FIG. 3.—Strike and dip.

The full statement of the position of a stratum accordingly takes the following form: strike N. 30 E., dip 50 SE.; or, since the direction of dip is at right angles to the strike, the position may be defined by writing: dip 50 S. 60 E., with equal accuracy and greater brevity.

Folding.—The original position of strata is nearly flat, as a rule, since it corresponds with the bottom of the basin in which they are laid down. An extensive coal bed is an example of extreme flatness corresponding with the level at which the vegetation grew. Deposits of mud or sand may accumulate on gently sloping bottoms, but the slopes are very gentle, usually less than two or three degrees from the horizontal. In spite of this originally flat and nearly horizontal attitude we find beds of coal or mudrock or sandstone or limestone bent and tilted. In the warping of the earth's surface they have sunk down or been raised up, and have thus been flexed from their original position. If subsequently compressed horizontally, they become more or less sharply folded up and down. Series of strata, often of very great thickness, thus come to lie in the form of basins and domes, troughs and arches, or closely compressed contortions. They have been flexed and folded after they were deposited.

Sir James Hall, a Scotch geologist, as far back as 1788 correctly observed and interpreted the convolutions of strata, and in 1812 he wrote as follows regarding his observations of the attitude of the rocks in the cliffs of the coast of Berwickshire, Scotland (Frontispiece):

> I reckoned sixteen distinct bendings in the course of about six miles, each of the largest size and reaching from top to bottom of the cliffs, their curvature being alternately concave and convex upwards. . . . These strata seem to have been originally deposited in a position nearly horizontal, and many of the particular beds possess that peculiar undulation on their surface which we meet with on a sandy beach, when the tide has left it, and which affords the most unequivocal indication of aqueous deposition. There is reason to believe also that the strata constituting these convolutions, though now detached from each other, have at one period lain in continuity and horizontally; that by the exertion of some powerful mechanical force they have been compelled to assume their present contorted shape; that their continuity still exists below, and would be seen, could we penetrate into the masses under the level of the sea; the interruption of their continuity upwards having

> arisen from a removal of part of the rock, by some of those revolutions, which have everywhere agitated and corroded the surface of our globe.
>
> In the year 1788 it occurred to me that this peculiar conformation might be accounted for by supposing that these strata, originally lying flat and in positions as nearly level as might be expected to result from the deposition of loose sand at the bottom of the sea, had been urged when in a soft, but tough and ductile state, by a powerful force acting horizontally; that this force had been opposed by an insurmountable resistance upon the opposite side of the beds,—or that the same effect had been produced by two forces acting in opposite directions; at the same time that the whole was held down by a superincumbent weight, which, however, was capable of being heaved up by a sufficiently powerful exertion.[1]

Sir James then described certain experiments which he made to test his theory by compressing layers of cloth horizontally under heavy weights. By this means he obtained folds sufficiently like those he had observed in the rocky strata to satisfy him that the process had been correctly interpreted. Anyone can make a similar observation by wrinkling a tablecloth or observing the character of the folds in his coat sleeve, but the folds in the cloth must be magnified from inches to tens of miles to equal those of the folded mountain ranges of the earth's crust.

In the century and a quarter which has elapsed since Sir James was the first to recognize the true character of rock folds, the study of their forms and of the mechanical conditions that control their development has become a technical branch of geology, and he would be puzzled, no doubt, to read current descriptions couched in terms that have become necessary to designate different kinds of folds or parts of them. In coal mining, in the development of oil fields, in metal mining, and in theoretical geology, the discrimination of different types is essential to an adequate understanding of the structures and of the various valuable deposits sometimes connected with them.

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[1] HALL, SIR JAMES, Bart., On the Vertical Position and Convolutions of Certain Strata and their Relation with Granite. *Trans.* Roy. Soc., Edinburgh, vol. VII, 1815.

Folds which are "alternately concave and convex upward" lie in alternation in any continuous, wrinkled layer, whether it be of cloth or of rock. Those which are convex upward rise as it were from the surface of those that are concave upward, and at their ends they fade out into the general flattish surface. A common form of wrinkles is that of a cigar sliced in half lengthwise. Folds are rarely isolated. They occur in groups. The strata are continuous beneath the surface of the ground, as Sir James inferred and as has been abundantly proved by mining operations. There would also be a continuous surface above ground, if erosion did not immediately attack any fold that begins to rise above a local or general base level, and wear away the up-arched strata. This fact of former continuity should not be forgotten as we proceed to dissect the once continuous structures into their parts.

Up-arched folds, those which are convex upward, are known as *anticlines*. Depressed folds, those which are concave upward, are called *synclines*.

These terms came into use early in the investigation of the contortions of strata, when geologists began to distinguish the various forms of flexures or folds they observed in the mountain ranges. De la Beche thus defined an anticline:[1]

> Anticlinal line is that line from which the strata dip on either side: the ridge of a housetop will convey an idea of this line, the slope of the roof representing the dip of the strata.

Syncline signifies the reverse of an anticline, that is, a basin or canoe shape, and *monocline* designates strata which dip in one direction only. These definitions and others are given in detail in the following section.

Where strata have been folded and the folds themselves have been pushed over, the arch of an anticline may be turned downwards or that of a syncline upwards. These are accidents of extreme folding which do not affect the definition that is based on the normal position of the folds.

[1] De la Beche, H. T., "Geological Manual," p. 507, 1832.

Folds and Their Parts.—The two great types of folds are the syncline and the anticline.

The syncline is the simplest type (Fig. 4). It is a depression of the strata from a flat to a basin-shaped form. In cross-section it may be shallow and gently rounded, or deep, straight sided, and sharply angular. Sometimes the sides are closely pinched together. In plan view a syncline may be oval or long, narrow, and acute at the ends. Geometrically a syncline is characterized by the fact that it is concave upward. Geologically it is determined by the presence of younger strata within the basins of the older.

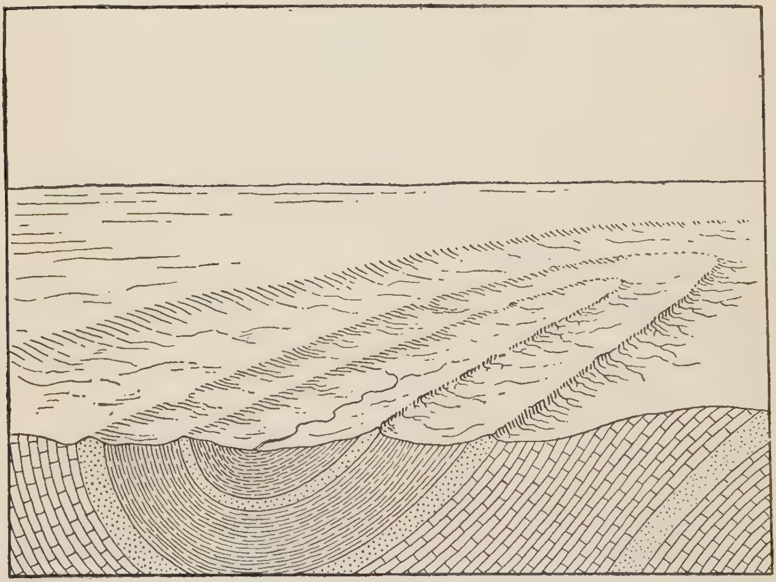

Fig. 4.—View of a syncline, showing the outcrop on the surface and a vertical cross-section.

The anticline or arch (Fig. 5) is the companion of the syncline. It is an elevation of the strata in a direction opposed to gravity, from a flat to a dome-like or half cigar-shaped form. The cross-section varies from a broad, gentle arch to an acute, straight-sided roof. In plan anticlines are often long and narrow. Geometrically the anticline is distinguished by its upward, convex curve. Geologically it is recognized by the presence of older strata within the arches of the younger.

Any syncline or anticline consists of two sides, which meet along the line of lowest depression in the syncline or along that of greatest elevation in the anticline. The sides may be called the limbs, slopes, flanks, branches, legs, or shanks. It is customary to regard an anticline as extending from the synclinal axis on one side to the parallel synclinal axis on the other side. Also it is usual to include in any syncline all the structure between two anticlinal axes. Thus every anticline consists of two half synclines, and every syncline consists of two half anticlines. (See Figs. 6–8.)

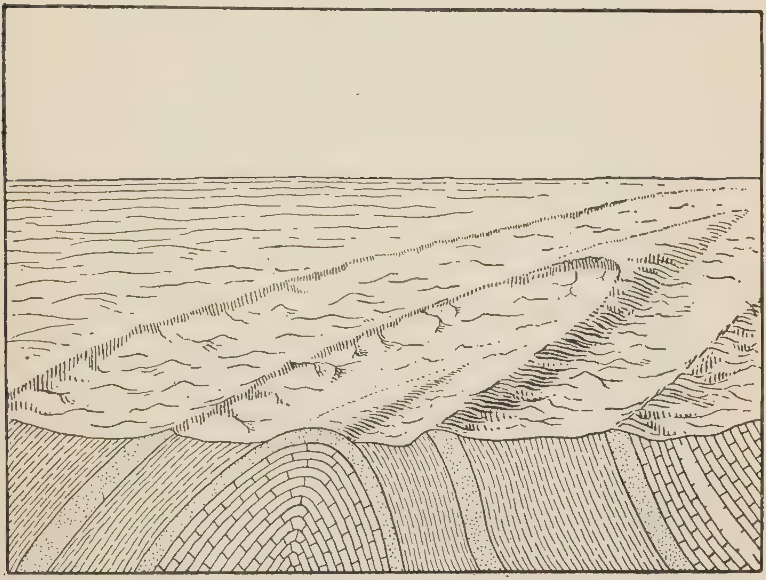

Fig. 5.—View of an anticline, showing the outcrop on the surface and a vertical cross-section.

In the last few lines we have referred to the axes of synclines and anticlines. The word axis is here used in the sense of a definite line of reference. In a syncline the axis is that line which connects the *lowest points of the trough along any one stratum.* In an anticline the axis is that line which connects the *highest points of the arch along any one stratum.* There is in every fold an axis for each and every stratum. Now if we think of the strata as infinitesimally thin, the axial lines will touch one another and will be the lines of the axial plane or surface.

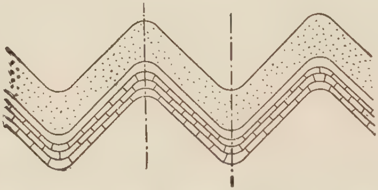

FIG. 6.—Upright symmetrical fold; the axial plane is vertical.

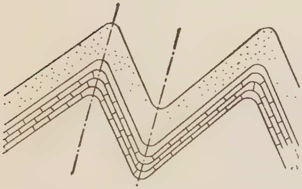

FIG. 7.—Unsymmetrical fold; the axial plane of a syncline is inclined toward the gentler dip, that of an anticline toward the steeper dip.

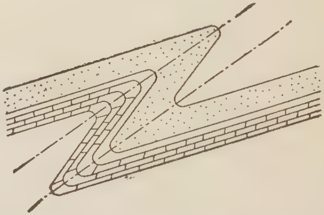

FIG. 8. -Overturned fold; the axial plane is inclined at a low angle.

FIGS. 6, 7, and 8.—Diagrams of folds showing the positions assumed by the axial planes, provided they be located at the points of maximum curvature.

The preceding statement may be put in another way, namely, the axial plane or surface of any fold is that plane which bisects the angle between the limbs of the fold.

The preceding definition of the axis and axial plane of a fold is correct and free from ambiguity when the fold is symmetrical or nearly so and is upright. But if a fold has been pushed forward until one limb is steeper than the other, the position of the axis, as thus defined, will have shifted. The original axis of an anticline comes to lie at a lower level than the highest point of the arch, and a new axis occupies that position. An alternative definition is sometimes used in that case, the axis being located at the point of *maximum curvature.* There is an advantage in that procedure, since the point remains fixed with reference to the limbs of the fold, whatever their changes of position may be. It also corresponds with a third definition, sometimes used, namely: the axis of a fold is the line formed by the *intersection of a stratum with a plane which bisects the angle* between the limbs of the fold.

For practical purposes—to locate an anticline in drilling for oil, for instance—the first definition is the most useful. In the mechanical analysis of structures the second and third are more definite. A usage sometimes met defines the axis as the intersection of a topographic surface by the plane that bisects the angle between the limbs. This is an accidental relation and the definition has no justification in exact practice.

By reference to Figs. 6, 7, and 8 it will be seen that if the strata dip equally on both sides of the fold the axial plane is vertical, but if the dip on one side of the fold is gentler than on the other the axial plane will be inclined in the direction of the gentler dip. This fact is sometimes of importance, as in drilling for oil, for instance, when the object may be to strike the axis of the fold at a depth of 3,000 or 4,000 feet.

In a preceding paragraph, page 24, we have defined the strike and dip of strata. We also speak of the strike of the axial plane of a fold or of the axis of a fold, meaning the bearing of a horizontal line drawn upon the axial plane. We may also speak of the dip of the axis, meaning the dip of the strata in the direction of the axis immediately on the crest of an anticline or in the bottom of a syncline; but it is better usage to substitute the word pitch for dip in speaking of the inclination of the axis, and thus to distinguish the pitch of the strata on the axis from the dip of the strata on the limbs of the fold.

It is important to recognize the relation which exists between

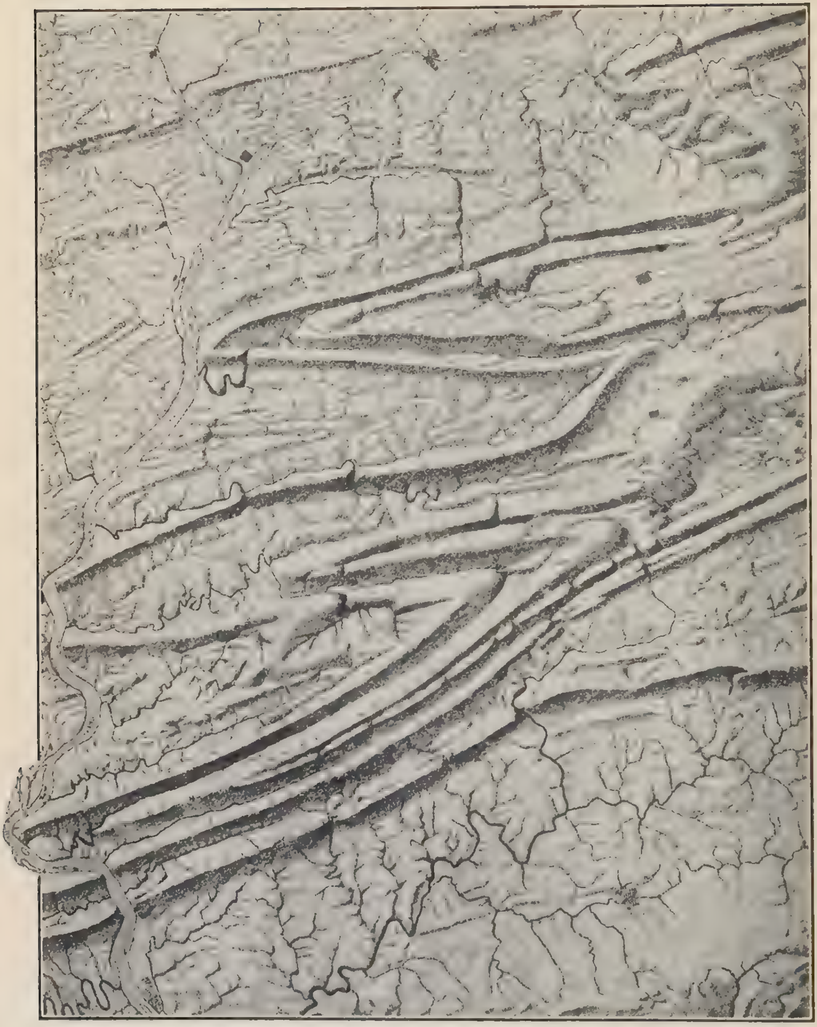

FIG. 9.—Structural plan of Northeastern Pennsylvania.

the strike of strata and the axes of folds. Where folds are long and narrow the strike of the strata often runs parallel with the axes of the anticlines and synclines for long distances. In the Appalachians, for instance, this parallelism may extend for two or three hundred miles. But as the beds approach the axis their strike turns toward it and crosses the axis, being at right angles to the strike of the axis itself at the point of crossing. Strata thus loop backward and forward alternately around synclinal and anticlinal axes.

Classification of Folds.—Folds are classified in four different ways: (*a*) By the relative amount of the opposed dips of the limbs; (*b*) by the form of cross-section, involving the relative thicknesses of any stratum on the limbs as compared with the axial regions; (*c*) by the degree of compression; and (*d*) according to the combination of anticlines and synclines.

(*a*) If we compare the opposed dips of any anticline or syncline, it is evident that they may be equal or unequal. If equal, we have a *symmetrical* fold; if unequal, an *unsymmetrical* one (Figs. 10–13). The amount of the dip is not involved in this distinction. Thus, the dips of a symmetrical anticline may be very gentle or may be vertical, but they must both be the same. In an unsymmetrical fold one limb may lie nearly flat, the other stand vertical, at right angles to it. The actual difference of dip between the two limbs may go even farther, the steeper dip passing the vertical and becoming overturned. In this way, in an extreme case, the overturned limb may become practically parallel with the upright limb, and we then have a completely overturned fold. These various folds are illustrated in Figs. 13, 16, and 17, and the special names describing each kind are given with the illustration.

(*b*) When strata are bent they may adopt *concentric* or *similar* curves, according to the mechanical conditions under which the folding occurs. When the strata bend *concentrically* they everywhere retain their individual thicknesses. The center of curvature remains constantly the same, but the radii of curvature increase from near the center outward. With the increase in radii the curves flatten. Thus concentric folds would die out upward and downward if the thickness of the strata were very great.

Concentric folds, as a rule, are formed as a result of unequal vertical subsidence or uplift rather than by horizontal pressure.

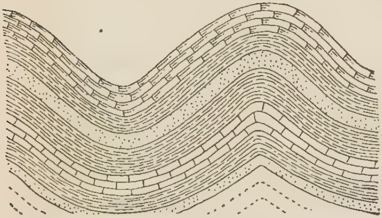

Fig. 10.—Symmetrical or upright fold, open.

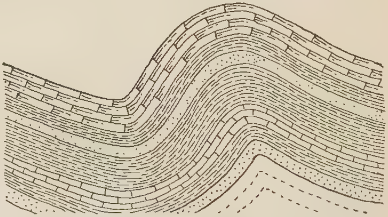

Fig. 11.—Unsymmetrical or inclined fold, open.

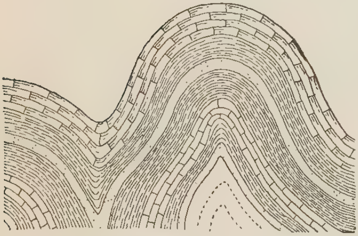

Fig. 12.—Symmetrical or upright fold, closed.

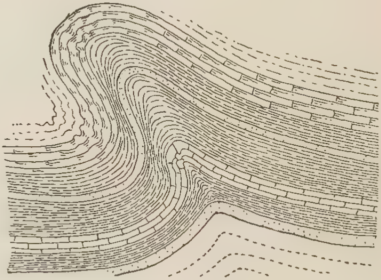

Fig. 13. —Unsymmetrical fold, closed and overturned.

Figs. 10–13.—Types of folds.

A special case occurs when strata are laid down over a rigid mass, which remains fixed in position or may be raised up during or after deposition. The strata dip away from it on both sides and form an anticlinal flexure. The beds thin on the axis, instead of on the limbs. The name "*compaction fold*" has been applied to certain examples, but this term covers only a special case and is not considered adequate to describe it unless the conditions of origin can be demonstrated. These facts are illustrated by the experiments of Nevin and Sherrill [1] on flexures formed by the compacting of sediments over topographic elevations.

Similar folds embrace equal angles between the limbs of successive strata. The curvature of the limbs is often very slight, and they lie parallel to one another, like the sides of many V's set one inside the other. The curvature is apt to be concentrated

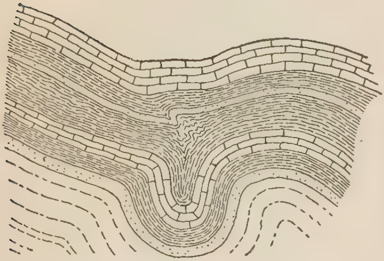

FIG. 14.—Syncline showing a keel; a carinate syncline.

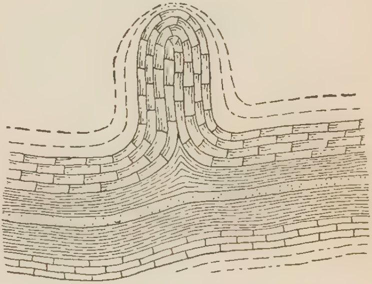

FIG. 15.—Carinate anticline, the lower strata remaining flat.

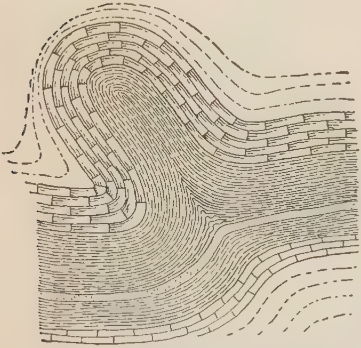

FIG. 16.—Carinate anticline, overturned.

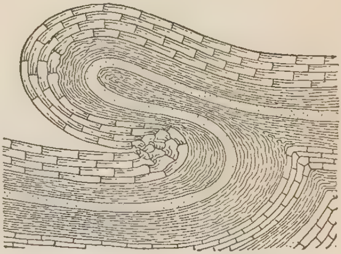

FIG. 17.—Carinate anticline, recumbent; or recumbent fold.

FIGS. 14–17.—Types of folds.

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[1] NEVIN, C. M. and SHERRILL, R. E., Studies in differential compaction, *Bull.* Am. Assoc Petr. Geologists, vol. 13, pp. 1–22, 1929.

in a short section, and is therefore more or less acute. The center of curvature for different strata is never the same. The distinguishing characteristic is that the strata are thinner on the limbs of the folds than they are between the crests of the anti-

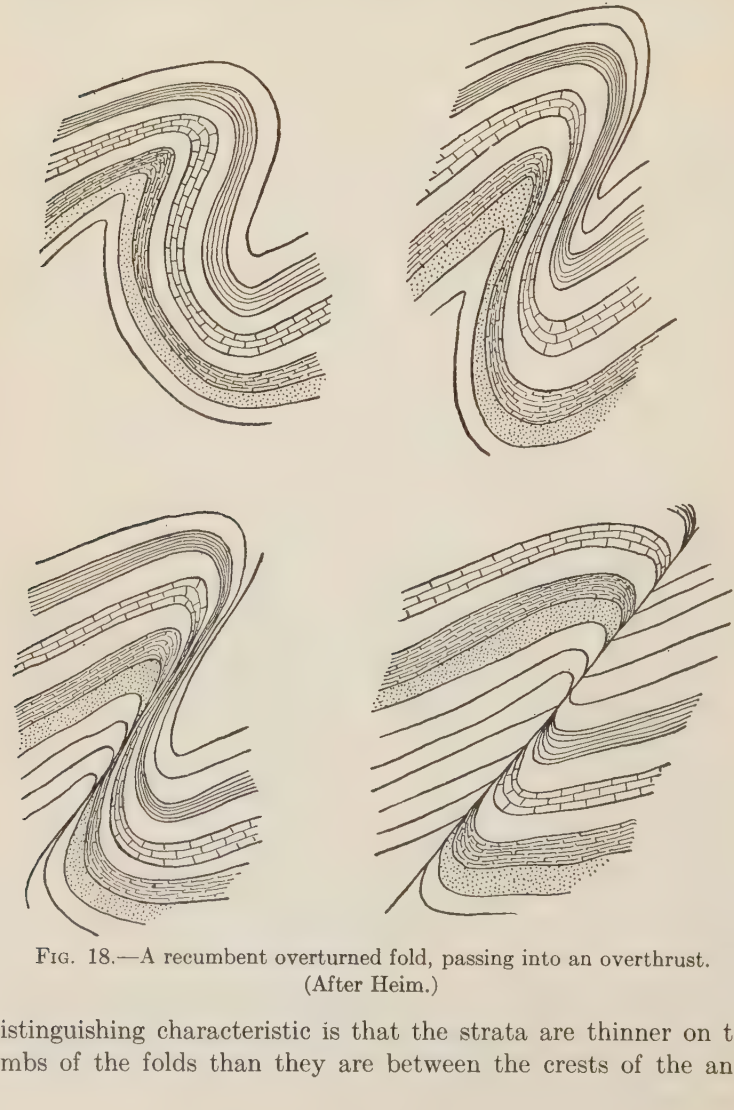


FIG. 18.—A recumbent overturned fold, passing into an overthrust. (After Heim.)

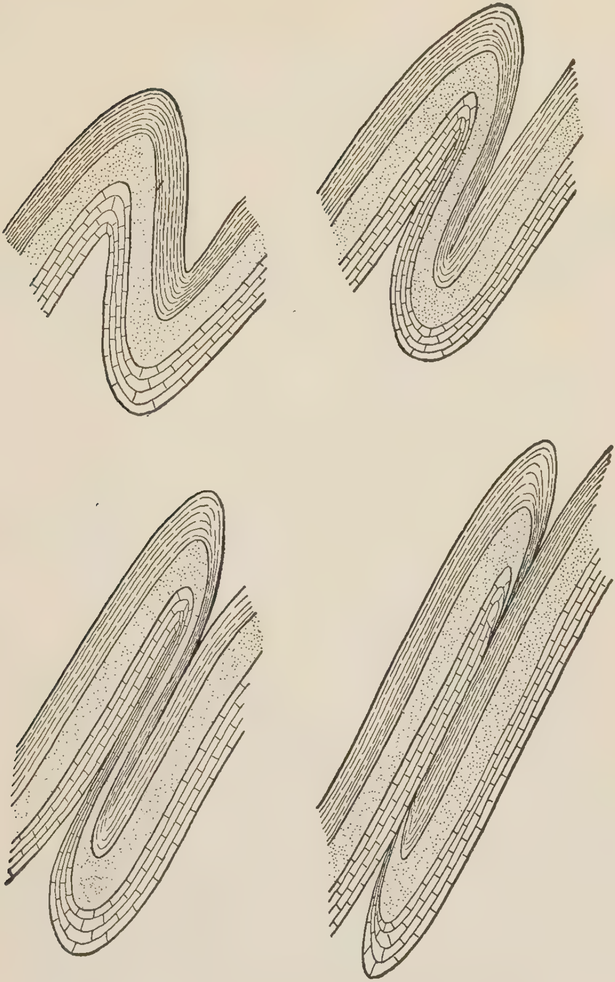


Fig. 19.—A recumbent fold with parallel limbs, passing into an overthrust. Note that the thrust fault is not marked by any change of dip. It can be recognized only by repetition of strata.

clines or the bottoms of the synclines. Natural folds usually approach the similar type, which is shown in the accompanying figures.

(*c*) Folds may be classified as *open*, *closed*, or *squeezed*, according to the degree of compression they have suffered. An open fold is one which may be bent closer without disturbing the parallelism of the strata on any limb (Figs. 10 and 11). A closed fold is one which cannot bend closer without distorting the bedding (Figs. 12–16). A squeezed fold is one in which the compression has gone so far as to alter materially the thickness and form of the strata or to shear them off (Figs. 17, 18, 19, and 23–27).

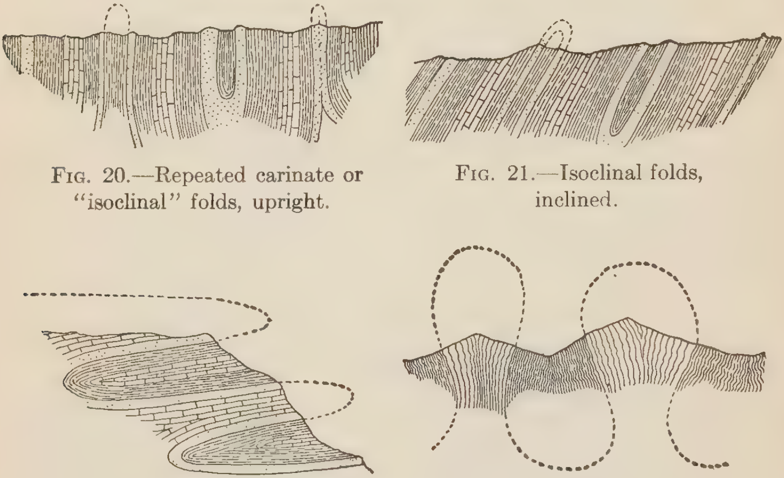


FIG. 20.—Repeated carinate or "isoclinal" folds, upright.

FIG. 21.—Isoclinal folds, inclined.

FIG. 22.—Isoclinal folds, recumbent.

FIG. 23.—Fan structure, upright.

FIGS. 20 to 23.—Types of folds, continued.

(*d*) Anticlines or synclines seldom occur as separate individuals. They are usually connected, lying side by side in alternation, uniting by convergence of several axes to form one, or dying out by the merging of an axis with the slope of a stratum. Thus it often happens that many anticlines and synclines are related to one another as parts of a *composite structure.* Indeed even those folds which we regard as simple are usually found to be composite in detail. That is, there are minor folds involved in their limbs.

Composite folds may be small or large. The microscope reveals folds which are parts of macroscopic folds, and even submicroscopic plications may occur in great detail. On the other hand, large simple folds, several miles across, are commonly parts of great composite structures which are nothing else than major folds. Thus size is not a condition of the idea of a composite structure.

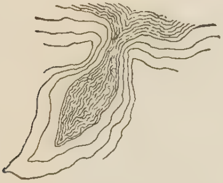


Fig. 24.—Squeezed syncline.

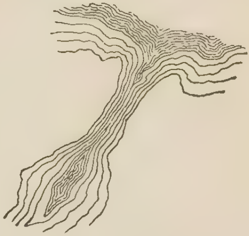


Fig. 25.—Squeezed syncline and detached core.

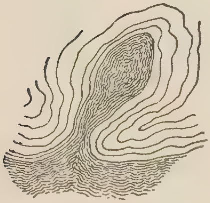


Fig. 26.—Squeezed anticline.

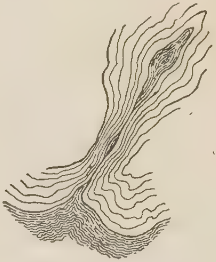
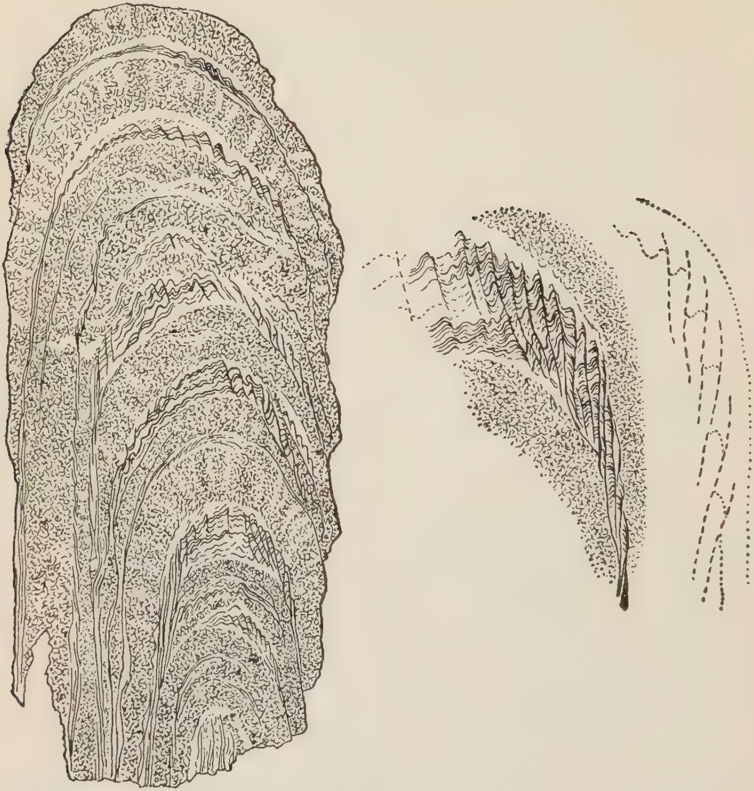


Fig. 27.—Squeezed anticline and detached core.

Figs. 24 to 27.—Types of folds, continued.
(After Heim and de Margerie.)

It is convenient to have names by which to distinguish different composite structures. Dana gave the name *synclinorium*



Figs. 28-29.—Folds in "Rothidolomit," a hard dolomitic limestone of the Alps. (After Heim. Mech. der Gebirgsbildung, Plate XV, Figs. 7 and 8.)

The specimen consists of layers of dense yellow dolomite and greenish clay slate. The latter appears more minutely crumpled, the former arched without crumpling.

Fig. 29 is an enlargement of part of Fig. 28.

In the process of folding the layers of dolomite worked as competent strata and determined the form of the folds. The slaty layers were incompetent and adjusted themselves to the interspaces.

to composite synclines of large dimensions.[1] A mountain range which exhibits a synclinal folded structure is a synclinorium. Or, if it have an anticlinal structure composed of many anticlines and synclines, it is appropriately called an *anticlinorium.* In a synclinorium the younger strata occupy the central position in the structure; in an anticlinorium it is the older rocks which are found there.

The terms *geosyncline* and *geanticline* are used to describe very large depressions or very large elevations of the earth's surface. Their use does not, however, imply that the rocks in the geosyncline or within the geanticline are folded. They may not even be stratified. Within a geanticline they may be massive rock, like granite, which cannot fold because it is not bedded. Or in a geosyncline they may be modern, flat-lying sediments as in the Valley of California. Thus " syncline " and " anticline " have lost their original meaning in this connection and merely indicate a trough or uplift, as the case may be.

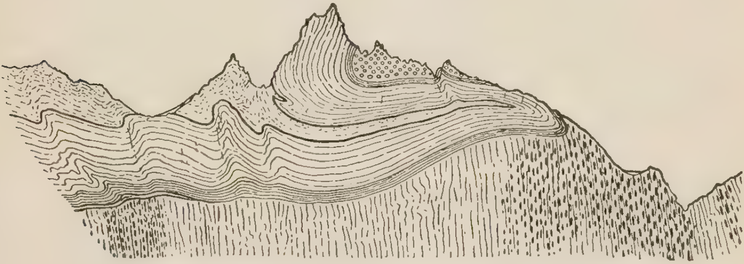


FIG. 30.—Overturned fold in the Alps. (After Heim.)

Note.—The facts by which the occurrence of folds may be recognized in nature are discussed in the chapter on Field Methods.

ZONES OF FOLDED STRATA

General Relations.—In various parts of the world there are long, relatively narrow zones in which stratified rocks occur with a more or less pronounced folded structure; that is, the strata have been bent into alternate anticlines and synclines of the kinds described in the preceding pages. There usually are certain general facts that are common to the history of all such folded zones. Thus:

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[1] DANA, J. D., "Manual of Geology," 4th ed., p. 380, 1895.

In most cases, in some early stage of its history, any such zone was part of a land area which had been very deeply eroded to the depth where crystalline intrusives and metamorphic rocks were exposed, and a peneplain had been more or less perfectly developed. During some later period warping ensued. A trough-like subsidence bordered an upwarp, and as the warping progressed erosion transferred the waste of the rising land to the trough. The latter was usually deep enough to be occupied by marine waters and the sediments were commonly marine rather than continental. Warping of the land area and of the trough continued to progress during a long time. The subsidence of the trough frequently amounted to many thousand feet, yet it was constantly filled or nearly filled with the accumulating sediment. After a long lapse of time the dynamic conditions changed. The forces which for so long had gradually raised one strip and depressed another were replaced or overpowered by intense compressive stresses, which acted horizontally and demonstrated their power by folding the strata that had accumulated in the trough. Although the process of folding undoubtedly occupied a geologic period, it was a very active movement in contrast to the excessively slow warping that had gone on during several preceding periods or a geologic era preceding.

The phenomena of warping, erosion and sedimentation, and folding have been repeated in the definite order described during various geologic ages and in many parts of the earth, in such manner that a relation of cause and effect is clearly shown. Several theories have been proposed to account for the sequence of changes, but we are not here concerned with them. The facts are illustrated by the following descriptions of typical zones of folding.

Appalachian Zone.—In pre-Cambrian time eastern North America appears to have been a land of somewhat greater area than at present and to have extended into what is now the western Atlantic basin, though probably not far. The topographic aspect of the land was that of a peneplain. The rocks exposed at the surface were gneisses. Hence it follows that previous uplifts had summed up a total elevation of many thousand feet, enabling erosion to reach the sub-surface layer of highly metamorphosed rocks, and that the upwarping had ceased at some period so long prior to the beginning of the Cambrian that a peneplain could develop upon the stable continental plateau.

Lower Cambrian strata occur in eastern Tennessee and elsewhere in the southern Appalachians and record the initial movements that warped the pre-Cambrian peneplain. Strata of successive periods of the Paleozoic era were deposited in the deepening and spreading trough. The subsidence was very unequal. The trough developed local basins and in the deepest of these the bottom sank to 30,000 feet below sea level, that is, to depths as great as those of the ocean deeps. But the basins and connecting straits were constantly so filled with sediment that the waters remained shallow. The trough was about 1,500 miles long and in general about 100 miles wide. The nearest existing approach to the geography of eastern North America during Paleozoic time is probably to be found in the relations of the island festoons and marginal seas along the eastern coast of Asia, from Kamchatka southward.

When at the close of the Paleozoic the stress conditions changed with the development of powerful compressive forces in the crust of the earth, the outlying border of the continent was sheared off and pushed westward against the strata that had accumulated to a thickness of many thousand feet in the trough. The strata were mechanically weak in resistance to lateral compression and they yielded by folding and by faulting. Where the trough had been 100 miles wide the strata that now represent it occupy a width of 65 miles; that is to say, the eastern lands were pushed 35 miles westward. This was, however, but a part of the whole displacement. The eastern strip itself was intensely compressed and the Atlantic basin was widened by considerably more than the shortening of the cross-section of the sediments in the trough.

The mechanical effects of the compression as developed in the strata are folds and thrust faults such as are described in the appropriate sections of this book and in greater detail in the works listed below.[1]

The Appalachian folded structure has long been regarded as the classic example of folding and as such is commonly regarded as typical of similar structures to be looked for in other parts of the world; but that is a mistake. It is indeed a remarkable example of simple folding on a very large scale, but it is so simple and so large that it is in these respects almost unique. In other regions folding and faulting are usually combined in relatively small individual structures and in a more complex manner.

The Jura Mountains.—In southeastern France and northwestern Switzerland the Jura mountains present a folded structure that consists of sequences of anticlines and synclines similar in form to those of the Appalachian province, but constituting a comparatively short and narrow group. The length of the Jura is about 200 miles (300 kilometers) and its maximum width 30 (50 kilometers), the plan being somewhat crescent-shaped.

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[1] HAYES, C. W., The Southern Appalachians, in "Physiography of the U.S." by Powell et al., pp. 305–366, 1896.

KEITH, ARTHUR, Structural Symmetry of North America. *Bull.* Geol. Soc. Am. Vol. 39, pp. 330–331, 1928; also several folios of the Geologic Atlas of the United States, covering parts of Tennessee and North Carolina.

ROGERS, H. D., The Geology of Pennsylvania, a government publication. 2 vols. and atlas, 1858.

SAFFORD, JAMES M., Geology of Tennessee, 1869.

STOSE, G. W., Mercersburg–Chambersburg, Folio No. 170., Geologic Atlas of the United States, 1909.

Ibid. Pawpaw-Hancock, Folio, No. 179., Geologic Atlas of the United States.

WILLIS, BAILEY, Mechanics of Appalachian Structure, *Thirteenth Annual Report,* U.S.G.S., pt. 2, 1893.

Ibid. The Northern Appalachians in "Physiography of the United States," Powell et al., pp. 169–202, 1896.

Ibid. Paleozoic Appalachia. Maryland Geol. Survey *Reports.*

Ibid. History of the Potomac River, U. S. Water Supply Paper, No. 192, pp. 7–22, 1907.

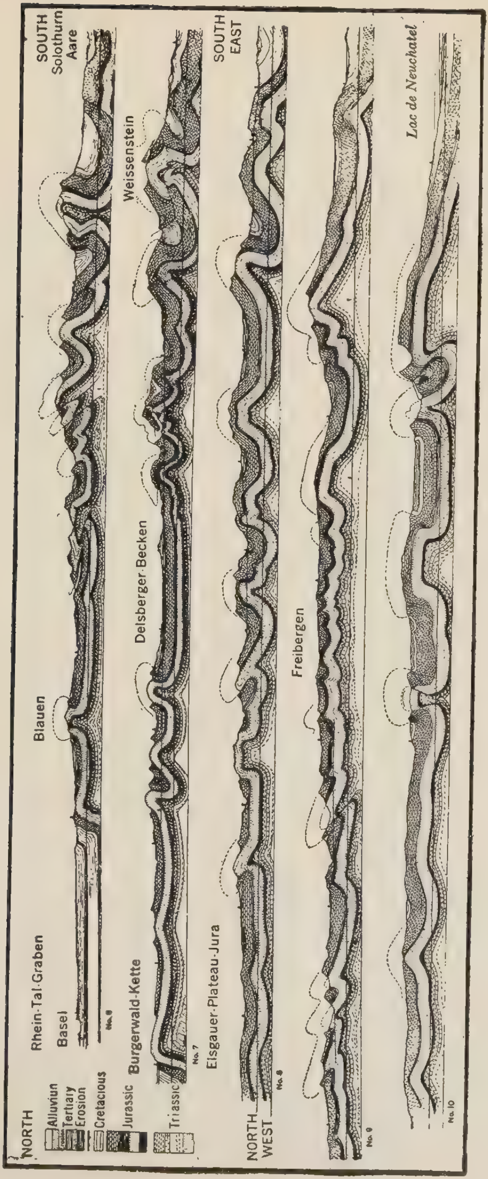

FIG. 31.—Sections through the middle Jura (Heim, Die Schweiz).

The history of the structure may be stated very broadly as follows: During the late Paleozoic extensive areas of central Europe presented the aspect of low lands, swamps, and shallow continental basins or seas. Erosion had worked deeply and warping had been slight. This condition persisted with some increase in the degree of warping during the Triassic and was succeeded by a general subsidence that permitted the Jurassic sea to occupy wide areas in France and Switzerland. Jurassic limestones constitute a great thickness of the strata involved in the Jura mountains, and the period derives its name from this circumstance. Up to the Cretaceous period or later the subsidence was somewhat uniform over large areas, but during the Cretaceous more pronounced warping resulted in the development of deep troughs and adjacent upwarps, so that the recently deposited calcareous sediments and some siliceous ones were exposed to erosion. A very characteristic formation, composed chiefly of clayey muds with more or less sandy beds intercalated in the shale, was laid down in the troughs to great thicknesses. It is known as the " Flysch " and ranges in age from Cretaceous to Oligocene. The difference in rigidity between the soft, weak strata of the Flysch and the hard, coherent limestones of the Jurassic and early Cretaceous had a pronounced influence upon the types of folds and thrusts that were afterward produced.

Toward the close of Miocene time the zone of the deep trough in which the Mesozoic and early Tertiary sediments had accumulated was subjected to the compression which had already begun to affect the Alps, and the strata were folded and dislocated. The characteristic anticlines and synclines which resulted from the pressures transmitted through strong limestone strata are shown in the accompanying sections taken from the exhaustive treatise on the Geology of Switzerland by the veteran geologist, Albert Heim.[1]

The Alps.—Among the folded zones of the world the Swiss Alps have long stood out as the type which served to illustrate

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[1] HEIM, ALBERT, "Die Geologie der Schweiz." In three volumes. Published by Chr. Herm. Tauchnitz, Berlin, 1919–1922.

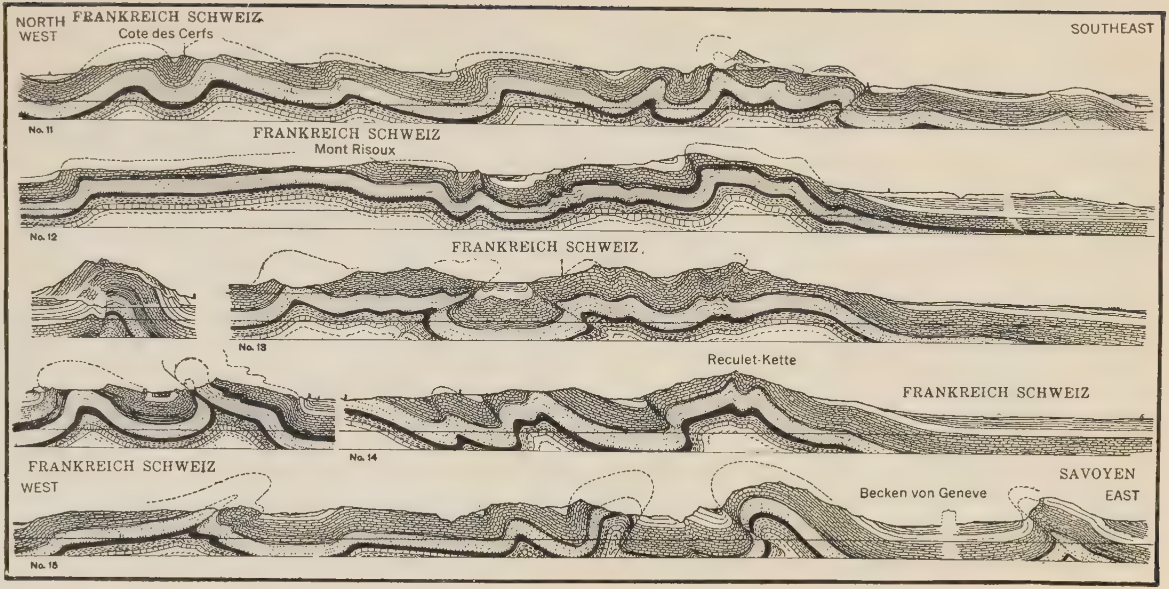

Fig. 32.—Sections through the southwest Jura (Heim, Die Schweiz).

the character of folded mountains and the mechanics of the process of structure. A long list of eminent geologists has contributed to give the Alps this reputation, but the conspicuous forms of the folds and overfolds are such that the structure itself has inspired the geologists. After the pioneers, Bernard Studer and Arnold Escher von der Linth, came their disciple, Albert Heim, whose Mechanismus de Gebirgsbildung, published in 1876, laid down the basic principles of structural geology, and he, after nearly half a century, has summed up the actual state of knowledge and theory in his great work, Die Geologie der Schweiz. A host of others have contributed to the intensive studies of the mountains and the development of ideas. Among them Maurice Lugeon is recognized as the founder of the present school of structural interpretation, which explains the facts of complicated folding and overthrusting by the theory of the so-called *Decken* or *nappes de recouvrement.* That theory is considered under the discussion of low-angle overthrusts (page 115). The folding itself is very extreme. Its character is in part due to the excessive degree of compression and in part to the association of rocks of the most diverse kinds, as has been stated. The structural type is illustrated in Figs. 30, 67, 68.

The history of the Alpine region of France, Switzerland, and Austria during the Mesozoic and early Tertiary was similar to that which has been stated for the Jura. The subsidence of the troughs was, however, more pronounced, the thickness of the muddy Flysch sediments and of the rigid limestones was greater, and the complexity of the overfolding was far more intricate in the Alps than in the Jura. The comparison of the two ranges throws a great deal of light upon the influence of stratification upon the development of folds, and also serves to show how differently neighboring sections of the earth's outer crust may be compressed.

CHAPTER 111

DIVISION OF ROCKS BY JOINTS

Definition of joints. Two classes recognized: compression and tension joints. Jointing by compression; description, occurrences; degrees of development. Jointing by tension; characteristics. Kinds of joints developed by cooling, torsion, folding. Causes of folding. Orientation of joints. Names of joints.

Definition.—A *joint* is a parting plane which separates or tends to separate two parts of a once continuous block.

The definition may be made more exact by stating that a joint is a purely mechanical effect, a shearing or tearing, and is distinct from the partings or tendencies to part that result from recrystallization. See Metamorphic structures, Chapter V.

Two Classes.—Mechanical jointing of a rock mass may result from compression or from tension. In the former case the rock is *sheared*. In the latter case the rock is *torn apart*. In the descriptions that follow we shall have occasion to recognize the fact that joints may be due either to compression or to tension, and that they thus fall into two major classes.

JOINTING BY COMPRESSION

Description.—Joints which have been produced by compression shear through the rock mass. The partings are characteristically smooth and their surface is usually a plane within the length and breadth of exposure. They occur spaced at short distances apart, the interval being sometimes as small as the fraction of an inch or occasionally as large as several hundred feet.

Sets of joints may be recognized. A set consists of joints that are parallel in strike and dip. There are generally two sets and

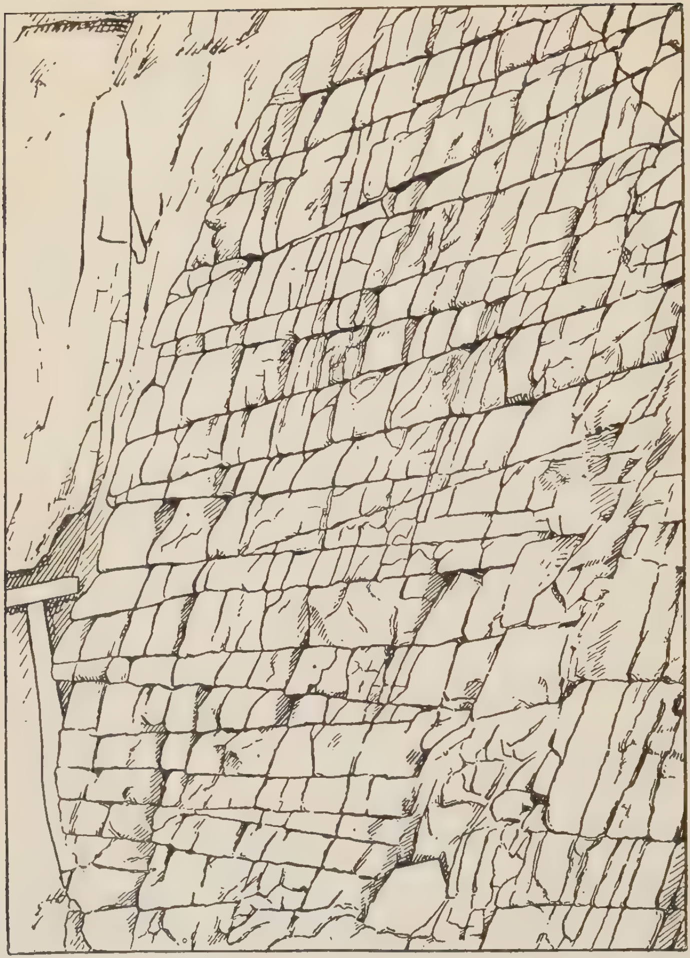

FIG. 33.—Joints in Greywacke, Currarie Port, South Ayrshire, Scotland. (Drawn from photograph in "Structural and Field Geology," by James Geikie, Plate XXXIV.)

Note the arrangement of the joints in two systems, the one from left to right, more strongly developed, the other up and down, less persistent. Minor diagonal joints are locally developed.

often three; there may be four or more. Three is a common number of sets because of a tendency on the part of forces and resistances to arrange themselves in three pairs, each of which controls a set of joints and may cause or prevent its development. The sets usually cut across one another at angles that vary from 90 to 100 degrees and thus block out nearly rectangular rhombs in the rock mass. Diagonal joints sometimes cut off the corners, producing triangular prisms or truncated pyramids.

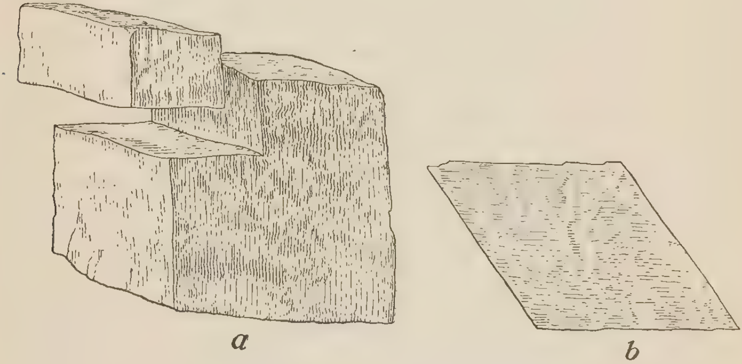

Fig. 34.—Drawing of specimen of jointed slate.

(*a*) Perspective view of block showing a piece detached on the parallel planes that traverse it according to the three systems of joints produced by pressure. Stratification does not affect either set of joints, the rock being homogeneous.

(*b*) Plan view of the joint block showing the great distortion of the ideal cube and the development of a rhomb by shearing along the joints.

Compression joints may be tight and invisible and become apparent only when loosened by shocks. Thus, blocks of granite 60 feet long were quarried in Maine and dressed to columns 6 feet in diameter without apparent fracture, but they parted when hung in a lathe, presumably because the dressing had weakened the adhesion of the widely spaced " blind " joints. In general, however, where they have been exposed to the action of air, water, and frost, joints are open, and it is evident that the superficial processes loosen the adhesion and separate the blocks.

Occurrence.—Compression joints occur in rocks of all kinds. In stratified rocks the planes of bedding frequently take the place of one set of joints. Two others commonly develop and these tend to stand at right angles to the bedding when the strata have not been bent or folded. Where strata are folded compression joints tend to develop during the process of folding, and they then cut the strata at a somewhat oblique angle to the bedding. The attitude of the oblique joints may give valuable information concerning the direction of movement of the beds in folding, and may serve to distinguish an anticline from a syncline. (See p. 235.)

Massive igneous rocks such as granite offer an excellent medium for the development of joints, because they are uniformly strong in all directions; in other words, they offer homogeneous resistances to deformation. They thus differ from the bedded rocks. In granite there is no pronounced internal parting to determine the orientation of shearing, and the three sets, if there be three, arrange themselves with reference to the dominant compressive stress.

Metamorphic rocks are cut by joint planes, which frequently cross the foliation of schists nearly at right angles. The relation of the jointing to the schistosity is then similar to the relation of jointing to stratification, both in angular position and in mechanical development. Stratification and foliation have in each case taken the place of a set of parallel joints, which supplement two other sets and thus help to define six-sided blocks.

Degrees of Development.—Joints vary greatly in perfection of development. They are most perfect in fine-grained homogeneous rock, such as clay rock. In that homogeneous material they are very smooth, continuous, and flat. They are often very closely spaced, so that the rock splits into thin sheets, the familiar slates commonly used for roofing. Slatey cleavage, as it is called, is an extreme development of mechanical shearing in closely spaced, parallel planes. The ease of cleavage may be promoted by the growth of flat crystals on the joint planes. Since slates are sedimentary rocks, bedding is always present as well as cleavage and the two may be parallel, but they may also cross each other at any angle up to 90 degrees. In the fine-grained clay rocks the bedding has not the same influence upon the direction of jointing as it has in sandstones or limestones, because the former shear with nearly equal ease in any direction.

The development of jointing in coarse-grained rocks or in rocks of irregular grain, such as conglomerates, is usually less perfect in that the joints are not so continuous and are not so strictly parallel as in the more homogeneous rock. Nevertheless, joints may cut smoothly even through the pebbles and matrix of coarse conglomerate. We then infer that the rock was confined on all sides by pressures of such magnitude that the adhesion between the pebbles and the matrix was equal to the cohesion within the pebbles and the whole mass was homogeneous in offering resistance to the shearing stresses.

Where two or more sets of joints are developed in a rock mass there is often one set which is more regular and more obvious than the others. It is so because the corresponding shearing stress met with less resistance than that encountered by the stresses in the other shearing planes. The stronger joint system develops in the direction of less resistance, other things being equal.

JOINTING BY TENSION

Characteristics.—The joints which have thus far been described and which include those that cut up masses of sedimentary rocks, massive igneous rocks, and metamorphic rocks belong to a general class of mechanical structures that are attributable to compression. There is another class of joints that result from tension.

In contrast to compression joints tension joints are apt to be irregular, uneven, or rough on the parting surfaces, and thus to show that the rock was torn rather than cut apart. Tension joints are characteristically open or gaping.

Jointing by Cooling.—The more conspicuous effects of tension in rocks are seen in those which have cooled and solidified from a molten state. In so cooling the masses contract and more or less pronounced tensile stresses are set up. Lavas frequently exhibit the effects in the form of joints on which the sheets divide more or less readily. These effects are described in Chapter IV.

Granite also exhibits tension joints which may be ascribed to cooling. They are irregular and frequently curved. They are thus distinguishable from the smooth joints which divide the masses on smooth planes and define more or less cleancut, rudely rectangular blocks. Those are attributed to compression. The tension joints, which are often invisible, are apt to open when the rock is exposed to changes of temperature. Thus, if a campfire is built against a solid granite boulder or cliff the rock will sometimes spall off with a sharp noise. Similarly, granite buildings crack and spall in fire. In granite quarries a tendency on the part of the rock to split parallel to the general contour of the ground is very commonly observed. The rift is called the " bed," but it has no relation to the bedding of sedimentary strata. In a similar manner large masses of granite often develop jointing parallel to their exposed surfaces. This effect is conspicuous in the Sierra Nevada, where it gives rise to the " dome " that characterizes the scenery in the vicinity of the Yosemite valley.

These domes are effects of tension, as was pointed out by Gilbert, who attributed the tendency to part on joints parallel to an exposed surface to heating, weathering, and dilation in consequence of unloading.[1] The last-named is probably the principal cause and is the reason why the dome structure is developed to so remarkable a degree in very large masses of granite and not in other rocks. Gilbert recalls the fact that granite when solidified from a molten condition is still at a very high temperature and after solidifying cools down through many hundred degrees. Internal tension results from contraction, but cannot produce parting of the rock so long as the mass is buried and confined under pressure. When the load has been removed by erosion the balance between compression and tension will be replaced by a tensile stress, which might become strong enough to cause jointing when it is supplemented by the strains induced by heating and cooling, or by weathering, or by all three conditions of change of volume near the surface.

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[1] GILBERT, G. K., Domes and Dome Structure in the High Sierra. *Bull. G. S. A.*, vol. 15, pp. 29–36, 1903.

Jointing by Torsion.—Torsion is cited by some geologists as a distinct cause of jointing. Daubree's[1] experiments on glass plates, which he broke along systems of joints by submitting them to a twisting stress, made the facts evident but without demonstrating the mechanical analysis of the stresses. Becker [2] has shown that the stresses set up by torsion act in the shearing planes at 45 degrees to the axis of torsion and are both compressional and tensile in character. The stressed substance yields to compression or torsion, according as it is weaker toward one or the other. Since rocks are generally weaker in resisting a tensile strain than in opposing compression it follows that joints produced by torsion are usually tension joints. Joints of this type are common in some districts and occur on large and small scales. They exhibit the characteristically irregular sides (having been torn apart) and frequently gape open. When filled with vein material they constitute gash veins, and the proper interpretation of the conditions of torsion and strain may be important as a clue to the distribution of the veins. Where such effects of tension exist there was also compression, developed simultaneously with the tension and approximately at right angles to it. It is hypothetically possible that torsion may set up tensile strains on a very large scale, in consequence of the rotation of elements of the earth's crust, and may produce a tendency to gaping or to actual gaps into which magmas are intruded. The arrangement of granite masses sometimes suggests this possibility, as in northern Japan.

Jointing by Folding.—Joints sometimes result from tension along the more sharply bent sections of folds in sedimentary rocks. It was once the prevailing belief that anticlines must split open along their axes in order to accommodate the tensile stress set up by bending; but it is now understood that the adjustment usually takes place in consequence of the sliding of the strata on the bedding planes. (See folding.) Nevertheless, it may happen in the bending of thick, rigid strata that tension is set up on the convex side of an anticline or syncline and that it may suffice to cause jointing. The joints are then aligned parallel to the elements of the cylinder or cone corresponding to the fold, and they cut through the strata nearly at right angles to the bedding but with a tendency to converge toward the center of the curvature of the fold. Another type of tension jointing is represented in Fig. 94. The tension is there shown as having developed from compression and folding, and the position of the tension joints, which are but slightly marked, is diagonal to the axis of the fold.

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[1] DAUBREE, G. A., "Geologie d'Experimentale," pp. 306–372.

[2] BECKER, G. F., The Torsional Theory of Joints. *Trans.* Am. Inst. Min. Eng., vol. 24, p. 136, 1895.

Causes of Jointing.—The causes of jointing have been much discussed and to some extent misunderstood. It is now recognized that all joints may be classed as results of compression or tension, as has been indicated in the preceding pages. The distinction between the two classes is not, however, always clear, and in some cases opinions may still differ regarding the conditions to any set of joints.

Becker very clearly presents the explanation of jointing considered as mechanical shearing under compression.[1] He shows that mass that is under compression will shear on a plane that is inclined at 45 degrees to the effective force and toward the side of the least resistance, in case there is one resistance which is the least. If there be two sides which offer equal resistances, two sets of shears may develop. They will both be inclined at 45 degrees to the effective force and at right angles to each other. If the resistances be equal on four sides, four sets of shears may develop simultaneously. The rock mass will be divided accordingly, it may be into parallel sheets, or into long rectangular prisms, or into four-sided pyramids joined at their bases. (See discussion of shearing, p. 226, Fig. 99.)

The theoretical angle of 45 degrees, which is the angle made by a plane of maximum shear with reference to the effective pressure, is seldom found in rocks, and the blocks usually have a slightly rhomboidal form with obtuse and acute angles approximating 95 to 100 degrees and 85 to 80 degrees, respectively. This is because the rocks yield by elastic compression and the shearing planes are spread before any actual parting can occur.

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[1] Becker, G. F., Simultaneous Joints. *Proceedings* Washington Academy of Sciences, vol. VII, pp. 267–275, 1905.

A tendency to shear may be imposed upon a rock without causing visible jointing. The molecules and crystals are then strained, as may be seen in polarized light, but the elastic limit of the rock has not been passed and it still looks unstrained. In order that visible joints should develop, the elastic limit must be exceeded by the strain; the rocks must part. This means that every visible joint is a plane of displacement, a fault of at least microscopic slip.

There is a theory that jointing of the type we have described as a result of compression may be produced by tension. Bucher [1] presents an argument based on an analogy with shearing in metals and demonstrates mathematically that shearing planes may result from tensile stress. The observations on metals and the mathematical analysis are unimpeachable, but the analogy with rocks is unsound because the resistances in the two kinds of material are different. Metals are relatively strong in tension and weak in compression; rocks are relatively strong in compression and weak in tension. The strength or weakness is in either case a relative capacity to resist stresses. Thus, if a rock be subjected to tensile stress it yields by tearing apart, because its cohesive strength is less than its shearing strength.

Becker distinguishes clearly between the two methods of parting. He wrote: [2]

> "One species of fracture takes place by tension and is usually characterized by sharp curvatures and uneven surfaces; the mass is *torn* asunder. The other method of fracture is by shearing motions due to pressure; the mass is *cut* to pieces by surfaces which are often, and indeed characteristically, flat and smooth."

A practical demonstration of the distinction between the effects of shearing and tearing apart in the case of rocks may be observed in tests on concrete. In the pressure machine concrete shears on diagonal planes. Under tension the specimen is torn apart on a break at right angles to the pull. The difference in strength under the two unlike stresses is such that we reinforce concrete by introducing steel bars to take the tensile stress, whereas we rely upon the concrete to withstand the compression.

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[1] Bucher, Walter H., The Mechanical Theory of Joints. *Journ. of Geology*, vol. XXVIII, pp. 707–730, 1921.

[2] Op. cit., p. 268.

Orientation of Joints.—The custom of designating the lay of a bedded rock by stating its strike and dip is conveniently extended to joint planes. The strike of a joint plane is the azimuth (compass course) of a level line in the plane. The dip of a joint plane is the angle between the joint plane and the horizontal, measured in a plane at right angles to the strike. Thus, in Fig. 3 the plane $WXYZ$ might be a joint plane and the strike and dip of the joint would be as shown.

Names of Joints.—It is convenient to distinguish sets of joints by their relation to the attitude of strata where the joints cut sedimentary beds. Thus:

1. A joint whose strike is parallel to the strike of a stratum is called a *strike joint.*

2. A joint whose strike is parallel to the plane of the dip (at right angles to the strike) of a sedimentary bed is called a *dip joint.*

Quarrymen distinguish the "bed," the "back," and the "end" joints in rocks. If the quarry is in sedimentary strata of sandstone or limestone, for instance, the bed is the plane of stratification, the back is a strike joint, and the end is a dip joint. In slates these relations are often too obscure to be recognized except by expert examination, and in massive rocks there is no strike or dip of bedding with which the strike and dip of jointing can be oriented. The use of the terms strike joint and dip joint is therefore restricted to joints in bedded rocks.

CHAPTER IV

DESCRIPTIONS OF FAULTS

General description. Statement of elementary facts. General descriptive terms relating to the fault itself and its relations in space. Normal and reverse faults considered with reference to relative movements and their definitions. Upthrusts and gravity faults described. Overthrusts and underthrusts compared. High-angle faults and low-angle faults distinguished. Normal faults described as features of plateau structure, of upthrust mountain structure, and of sunken areas. Fault troughs or graben, non-committal terms, not denoting origin as here used. Alternative displacements. The Unkar wedge. Rheingraben; views of various geologists; plateaus raised, valley block depressed. Jordan-Akaba or Dead Sea trough; rift valley or ramp valley. African Rift valleys; Lake Victoria Nyanza; Eastern and western rifts, volcanoes; Nyanza structure as a whole. Low-angle overthrusts; Appalachian thrusts; Rocky Mountain thrusts; Highland structure. Alpine structure. Low-angle underthrusts; underthrust folds; major underthrusts; sub-continental underthrusts.

GENERAL DESCRIPTION

Think of any mass of rock or of a stratum or vein which was once continuous and imagine it to be cut in two parts that are offset with reference to each other. It is then said to be faulted. The dividing plane is called a *fault plane*. The offset is called the *displacement*. The combination of the fault plane and the displacement constitutes a *fault*.

This imaginary case is often met in reality in geologic surveying and in mining. A geologist observes that a ridge which corresponds with the outcrop of a hard stratum ends abruptly, but that a similar ridge corresponding with the same stratum continues in an offset position with reference to the first (Fig. 36). If the identity of the strata is proved he may reasonably assume that a fault cuts across the series of strata of which the hard stratum is one and that the blocks that are thus cut apart have been pushed past each other. The outcrop of the fault itself is too commonly hidden under the alluvium of a valley, but may be found crossing some ridge or spur.

In underground work a fault may be crossed unnoticed where it is a tight fissure between similar rocks; or it may be found as a fractured zone full of water; or a vein on which a miner is driving a gangway may end abruptly against a blank wall. There the wall is the fault plane and the question which confronts the miner is which way has the vein jumped.

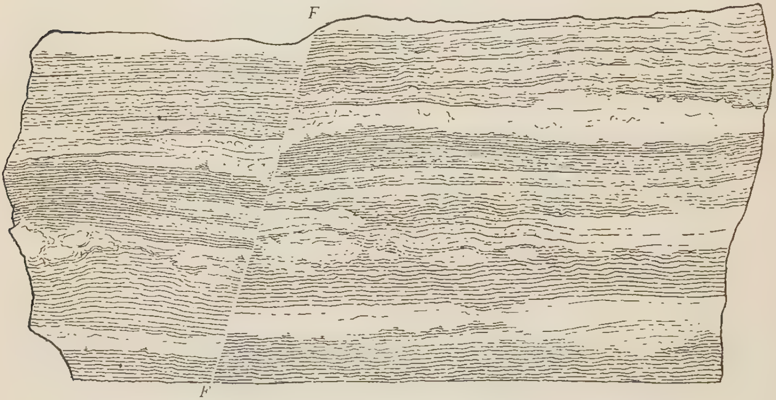


Fig. 35.—A fault in bedded rock. *FF* is the line of the fault, where the fault plane cuts the surface of the rock. (Drawn from specimen of bedded volcanic rock from near Lake Tahoe, Sierra Nevada, California.)

Faults are of all lengths, from those that are measured by miles down to those that can be detected in finely crystalline rock only with a high-power microscope. The dimensions commonly stated are the length of the outcrop and the amount of the displacement. The first can be stated only for faults that are large enough to be traced upon the surface of the earth. A fault is short if it is only a few miles long; it is in the class of large faults when its length is a hundred miles or more.

Displacements may be measured in any one of several directions, but commonly the practice is to state either the horizontal displacement along the fault or the vertical displacement across it. Thus, the ridge in Fig. 36 might be offset hundreds or thousands of feet and the fault would be said to have a displacement along the strike of that amount. Or, if a surface can be identified as having been continuous before faulting occurred and its relative elevations across the fault can be compared, then the difference of elevation between them may be said to be the vertical displacement of the fault. These phrases lack mathematical precision and are therefore useful only for the purposes of general description. More exact terms are necessary for technical discussions. (See pages 145, 171.)

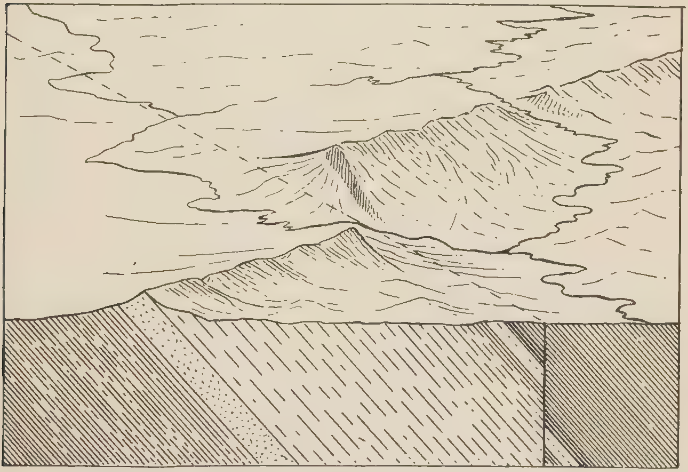


Fig. 36.—View of a fault, showing the effect on the topography and a vertical section.

ELEMENTARY FACTS

A fault is never an accident. It is always an effect of forces that have been in action in the earth's crust, and its meaning can be found in terms of those forces by the application of mechanical principles to its characteristics. We may thus deduce conclusions that are of significant importance in the study of terrestrial mechanics and in mining operations.

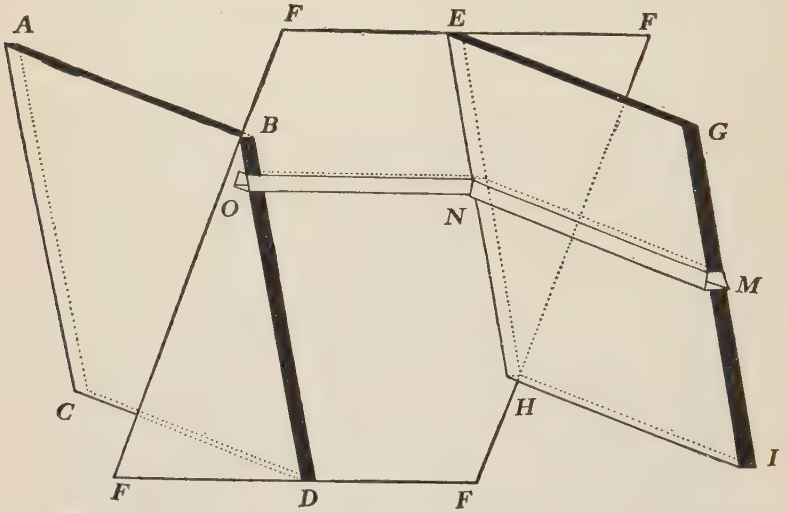


FIG. 37.—Perspective diagram showing a vein which is crossed and thrown to the left by a fault plane. The miner, having driven a gangway on the vein to the fault, recovers the vein by driving a cross-cut tunnel along the fault plane.

FF is the fault plane.

EGIH and *ABCD* are the sections of the vein.

MN is the gangway.

NO is the cross-cut tunnel.

If the miner had turned to the right, instead of to the left, at *N*, he would not have found the vein.

The existence of a fault is recognized in geologic surveying as in mining by the fact that a stratum or group of strata or a vein, which should extend further, is cut off abruptly. That portion which we have followed ends at the fault plane. The continuation extends beyond the fault plane, but it is offset. Theoretically the offset may be in any direction whatever. The offset may be up or down, or diagonally up or down, or horizontal. There is offhand no reason to assume an offset in one direction rather than in another.

A simple illustration of a practical problem of this kind is suggested in Fig. 37. A miner, having followed a vein by driving a gangway from *M* to *N* encounters the fault plane *FF*. How is he to know that the continuation of the vein will be discovered by driving a crosscut to the left, i.e., from *N* to *O*, rather than to the right? The answer is to be found in the discussion of the geometric relations of faults and of special criteria for determining the direction of movement on a fault plane. (See pages 131, 145.)

GENERAL DESCRIPTIVE TERMS

The Fault Itself.—The break or shear along which displacement takes place is a surface and is called the *fault surface* or *fault plane.* If the break is irregular and the corresponding fissure is a wide one, the fault plane becomes a *fault zone.*

The term fault plane is in common use for curved fault surfaces and for comparatively thick fault zones, it being understood that departures from a mathematical plane occur but are relatively slight for a small section as compared with the magnitude of the length and depth of faults.

Broken rock filling a fault zone is called a *fault breccia.* The same material, if finely ground, is called *fault gouge.* The latter is usually a slippery mud, which coats the surfaces of the fissure or cements the breccia.

Hade, Dip, and Strike.—The angle which a fault plane makes with a vertical plane (Fig. 38) is called the *hade* of the fault. It is an old mining term and its use illustrates the miner's habit of referring to the vertical shaft as a line from which to measure the attitude of any other line or plane. Geologists, on the other hand, habitually refer angles to a horizontal plane, and they speak of the *dip* of a fault (Fig. 38). The angle of hade and the angle of dip of any fault are complements of one another, their sum being 90 degrees. The smaller the hade the steeper the dip, and the gentler the dip the greater the hade. The word hade is also used as a verb, *to hade* meaning to incline toward.

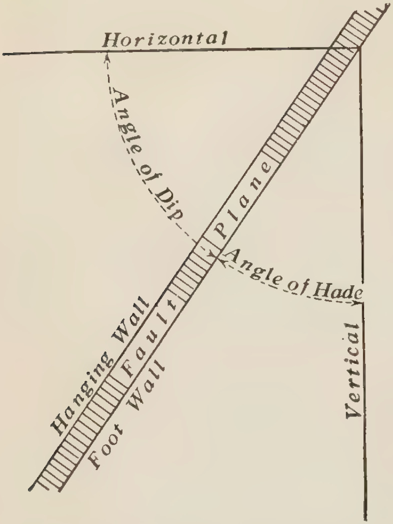


FIG. 38.—Diagram of the elements of a fault and the angles which define its position.

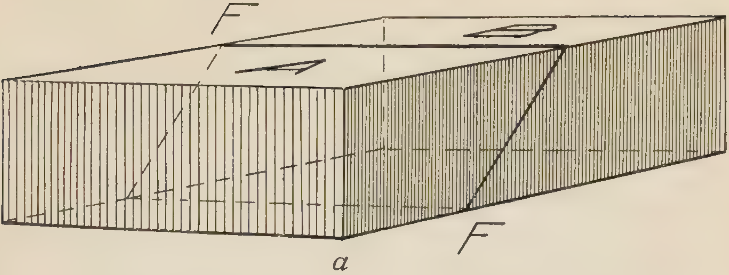
The term *strike* is used in connection with faults as it is with strata, to designate the direction of a fault outcrop. Specifically, the strike of a fault is the bearing of the trace of the fault plane with the horizontal plane.

When a fault plane is inclined so that one of the displaced parts lies above it, that part is called the *hanging* and its surface along the fault plane is the *hanging wall.* Similarly, that part which lies beneath the fault is called the *foot* and its surface along the fault is the *foot wall* (Fig. 38). These terms originated in mining and their significance is obvious as meaning that which hung above the miner or that upon which he stood.

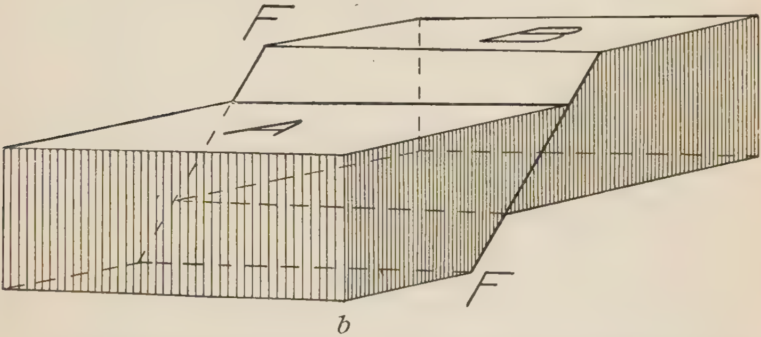
NORMAL AND REVERSE FAULTS

Relative Movements.—Consider Figs. 39, *a*, *b*, and *c*. In Fig. 39*a*, a mass is represented as divided by a shearing plane, *FF*. There is no displacement of the two parts of the mass and consequently no fault.

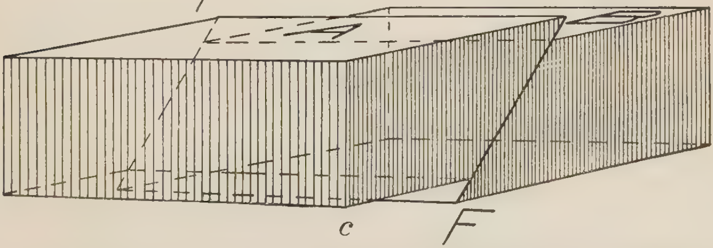
In Fig. 39*b* the mass is represented as having been faulted and the displacement may be explained in either one of three ways; namely:



(*a*) Block divided by shear plane without visible dislocation.



(*b*) Normal fault: block *A* may have slipped down (gravity fault) or block *B* may have been pushed up (upthrust).



(*c*) Reverse fault: block *A* may have been pushed up (overthrust) or block *B* may have been pushed under (underthrust).

FIG. 39.—Normal and reverse faults.

1. Part *B* has stood fixed while part *A* has slipped down; or
2. Part *A* has stood fixed while part *B* has been pushed up; or
3. Part *A* has slipped down while part *B* has been pushed up.

The vertical movements in any one of the three cases must have been accompanied by horizontal movements; namely:

If *B* stood fixed while *A* slipped down, then *A* moved horizontally forward.

If *A* stood fixed while *B* moved up, then *B* moved horizontally backward.

If both *A* and *B* shared in the vertical movement, then each probably took part in the horizontal movement also, but either one might have remained horizontally fixed while the other took all the horizontal movement.

In Fig. 39*c* the mass is again represented as having been faulted and again the displacement may be explained in either one of three ways; namely:

4. Part *B* has stood fixed while part *A* has been pushed over; or
5. Part *A* has stood fixed while part *B* has been pushed under; or
6. Part *A* has been pushed over while part *B* has been pushed under.

The horizontal movements producing elongation or shortening in these three cases must have been accompanied by vertical movements; thus:

If *B* stood fixed while *A* was pushed over, then *A* moved backward; or

If *A* stood fixed while *B* was pushed under, then *B* moved forward; or

If *A* and *B* were simultaneously pushed over and under, then each probably took part in the vertical movement also, but either one might have remained vertically fixed while the other took all of the vertical movement.

It thus appears that Fig. 39*b* represents either one of three possible movements of which the effect is the same, but in all cases the fault produced is of the normal type.

Fig. 39*c* also represents three possible movements with the same effect. In this case the fault produced is of the reverse type.

The original meaning of the terms *normal* and *reverse* was exactly the meaning of the words in common English. English coal miners encountered many more faults of the kind represented by Fig. 39*b* than of those represented by 39*c*, and they therefore called the former normal. A fault which was the reverse of normal was a reverse fault. These old terms have outlived their usefulness and have gathered a number of misconceptions, but they are so firmly fixed in the nomenclature of geology that they must be continued in use, though we should try to avoid the false interpretations with which they are too often associated.

Definition of Normal Fault.—A *normal fault* is one which hades to the apparent downthrow.

Examine Fig. 39*b*. It will be observed that the fault plane *FF* slopes under the block *A*, which has slipped down if *B* remained fixed. The subconscious idea that the displacement has necessarily been produced by the slipping of *A* has led to giving *A* the characterization of the *downthrown block* or *downthrow*. The definition usually given accepts that conclusion by leaving out the word *apparent*, which is here introduced because there is the alternative case in which *A* has not been thrown down, but *B* has been pushed up.

Definition of Reverse Fault.—A *reverse fault* is one which hades to the apparent upthrow.

Examine Fig. 39*c*. It is evident that the fault plane slopes under the block *A*, which has been pushed up if *B* remained fixed. We think of *A* as having been pushed up or as being the *upthrow* and define the type of fault accordingly, but we should not forget that *A* may have been the fixed block and *B* may have been pushed under it.

Gravity Faults.—The normal fault which hades to the *true* downthrow is an effect of gravity. It is the first case given above, in which *A* has slipped down while *B* stood still. In order that gravity may have been able to cause block *A* to slip down two conditions must have been satisfied: there must have been a lack of support under *A* and there must have been room for horizontal extension by the forward movement of *A*.

Landslides are one form of typical gravity faults. The type is illustrated on a small scale in the hand specimen of limestone shown in Fig. 40. The diagram, Fig. 41, shows the effect of similar faulting on a larger scale, such as is not uncommon in heavy basalt flows. Note that the upper surface is tilted back toward the fault in consequence of the rotation of the sliding block as it moved down the curved fault. The downward slipping cannot occur unless the horizontal movement is made possible by removal of supporting masses at the side, as when a river deepens its canyon or as hap-

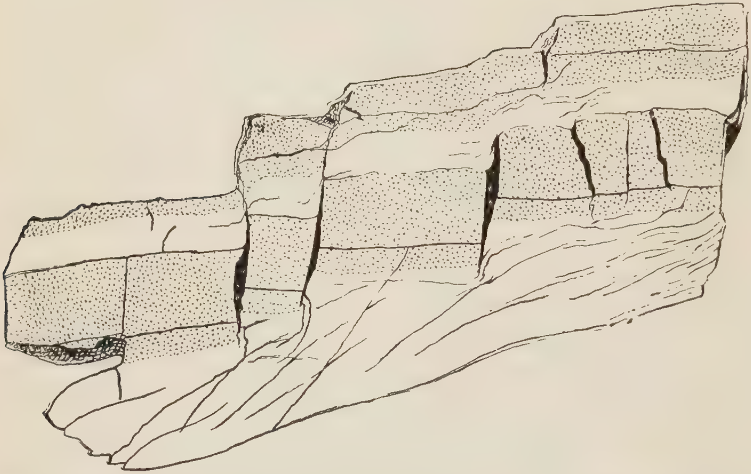


FIG. 40.—Normal faults in early Paleozoic limestone, Wacoba Canyon, Inyo Range, California. (Collected by C. D. Walcott.) The dotted layers are brittle limestone. The white layers are more clayey limestone and are less brittle.

The specimen demonstrates the limitation of fractures and accompanying faulting to the brittle layers. It shows how the blocks have tipped by slipping on the clayey base, leaving openings (black).

Size of specimen 2 inches by 5 inches. If we substitute miles for inches, the section would represent a section across mountain ridges produced by normal faulting.

pened when the Panama canal was dug. The digging of the canal removed the lateral support of the hills and they have been sliding in with irresistible movement.

In consequence of the tilting toward the fault the surface drains into it. Sometimes a lake forms; in any case the water lubricates the fault and promotes further sliding.

Gravity faults may also develop in consequence of removal of support from under a block, as by extrusion of molten magma.

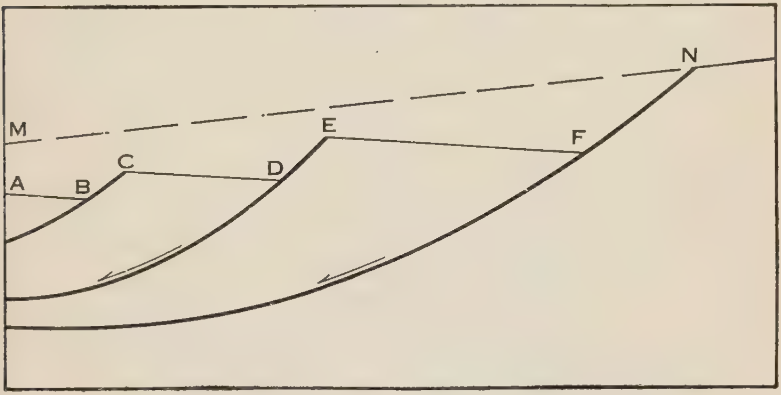


Fig. 41.—Diagram of displacement on normal faults of the landslide type, gravity faults.

Let *MN* represent the original surface and *AB*, *CD* and *EF* sections of the surface after faulting. The latter are inclined toward the fault in consequence of rotation of the masses on the curved fault surface.

The mechanism of their formation is discussed in connection with the subject of sunken or trough valleys. (Pages 76–100.)

Upthrusts.—Broad mountains or plateaus are often characterized by upthrusting. They result from the action of forces which are opposed to gravity and are sufficiently powerful to overcome it. The source of those forces is to be found in horizontal compression, which may operate in either one of two ways or in some combination of them. Thus, horizontal compression may produce a shearing plane which curves from considerable depth upward

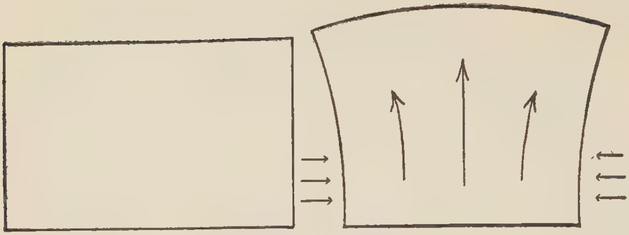


FIG. 42.—Horizontal shortening and vertical elongation. Sierra Nevada (California) type of structure. The two figures have the same area. The change of form is assumed to occur without change of volume. Deep-seated compression results in vertical extension and consequently in doming of the surface. The internal deformation may be by shearing or by development of vertical schistosity.

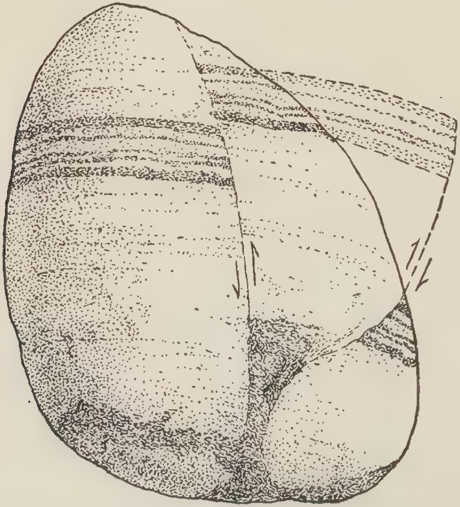


FIG. 43a.—Shearing and faulting in sandstone. Drawn from a pebble found in Cadrona Valley, South Island, New Zealand. Illustrates shortening in the direction of bedding, elongation across the bedding, and flowage of soft shale (dark) in following up the sandstone wedge. (Collector, Bailey Willis. Specimen in Stanford University collection.)

toward the surface. Displacement on such a plane is the reverse of a landslide. Its effect can be understood by reversing the arrows in Fig. 41. Upward movement of the blocks on the curved base must then result in tilting the upper surfaces away from the fault, in the opposite slope from that caused by down-sliding. This distinction affords an important means of determining whether a given change of position has been due to down-sliding or upthrusting.

The other way in which horizontal compression may act to lift masses against gravity is by changing the form of the deeper-seated section. Assuming that there is no significant change of volume and that the horizontal dimension of a mass is shortened, the mass must elongate vertically. The elongation will usually push upward and raise the surface. This is an important cause of warping. (Figs. 42 and 43.)

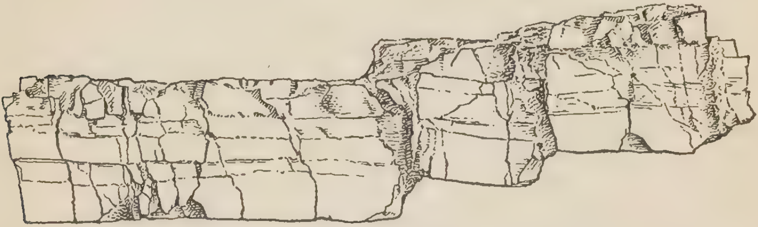


FIG. 43*b*.—High angle thrust faults in limestone, exhibiting intense crushing. (Specimen in the Stanford collection.)

Upthrusting is illustrated on a small scale in Figs. 43*a* and 43*b*, drawn from hand specimens. They should be compared with Fig.40 to bring out the contrast in the action of the forces in the two examples, which are no less significant because they represent the distortion of blocks only a few inches in length.

HIGH-ANGLE FAULTS AND LOW-ANGLE FAULTS

Non-committal Terms.—The preceding account of faulting describes the effects of forces which act either vertically in compression and horizontally in extension or, on the other hand, act horizontally in compression and vertically in extension. The contrast is between gravity and tangential compression. The two produce similar results of warping, of mountain uplift and trough subsidence, and of mechanical deformation in rock masses. They are difficult to distinguish and it is often desirable to describe the observed facts in any particular case without saying that they are due to the action of gravity or of tangential compression. The terms normal fault and reverse fault have come to have definite implications of this kind, the former being interpreted as an effect of gravity, the latter as resulting from compression in a horizontal direction. To avoid them we need non-committal terms.

The terms *high-angle fault* and *low-angle fault* are here introduced for that use. In the following descriptions of faulted regions the designation high-angle will be employed for faults whose attitude is steep; that is, they have a hade which is less than 45 degrees or a dip that exceeds 45 degrees. Low-angle, on the other hand, will be used to designate that class of faults whose hade is greater or their dip less than 45 degrees.

This distinction is simply one of position and has nothing to do with the nature of the fault, whether normal or reverse, since there are reverse high-angle faults and also normal high-angle faults, and low-angle faults may be either reverse or normal. The position of the fault plane with reference to the vertical or horizontal does not indicate the character of the force, whether tensional or compressional, to which the displacement was due. Thus the terms high-angle and low-angle are free from any ambiguity or undesirable implication as to the causes of faulting. They represent an observed fact and they express an important geometric relation, which fixes the trace of the fault outcrop on the topographic surface or the extension of the fault underground.

High Plateau Type.—High-angle, normal faulting of a large and simple type is characteristic of plateaus. It is there associated with and developed from monoclinal flexures. Gilbert, Powell, and Dutton were the first among American geologists to observe this relation.

Dutton [1] says:

> The great structural features of the High Plateaus are the faults and monoclinal flexures. . . . All of the greater displacements of the district present certain well-known habitudes. Most important among them is the strict homology of the faults with the monoclinal flexures. In truth, so close is the homology, that we are justified in calling a monocline in some of its aspects a modified fault. The only difference for structural purposes is that in the case of a typical fault of the simplest form the shearing is along one plane, while in a monoclinal the shearing lies between two planes. We also have cumulative or repetitive or "step-faults," where the shearing is subdivided among several planes. All have this in common, that the passage from the uplifted to the lowest thrown side is through a very narrow zone, which has its width reduced to zero in the case of a single or simple fault. All of the great lines of displacement assume all of these modifications in different parts of their extent. In one place the fault is simple. A few miles further along its course it may become subdivided into a series of step-faults; still further on, into a perfect unbroken monoclinal; it may be at another locality a faulted monoclinal—a part of the displacement being through flexing and a part through shearing. In any case the effect in its broader aspects is the same. One side has been uplifted, the other side "thrown." Another striking characteristic of these displacements is their systematic arrangement. Viewed in one way they approach parallelism, but there is a noticeable convergence of the lines as we trace them from south to north. . . . In the Grand Canyon district (where they give origin to the Kaibabs) the belt of faulted country is wider and the intervals between the faults and flexures are greater than in the High Plateaus. This width diminishes northward, and several of the grander faults at length become merged into one vast monoclinal flexure, forming the western flank of the Wasatch Plateau.

The magnitude of the faults is great. They vary in length from a score of miles to 300 miles or more, and their displacements attain as great a vertical throw as 2½ miles.

The displacement varies from zero to a maximum on any par-

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[1] Dutton, C. E., Report on the Geology of the High Plateaus of Utah, Dept. of the Interior, U. S. Geog. and Geol. Survey of the Rocky Mountain Region, J. W. Powell in charge, Chap. II, p. 25 et. seq., 1880

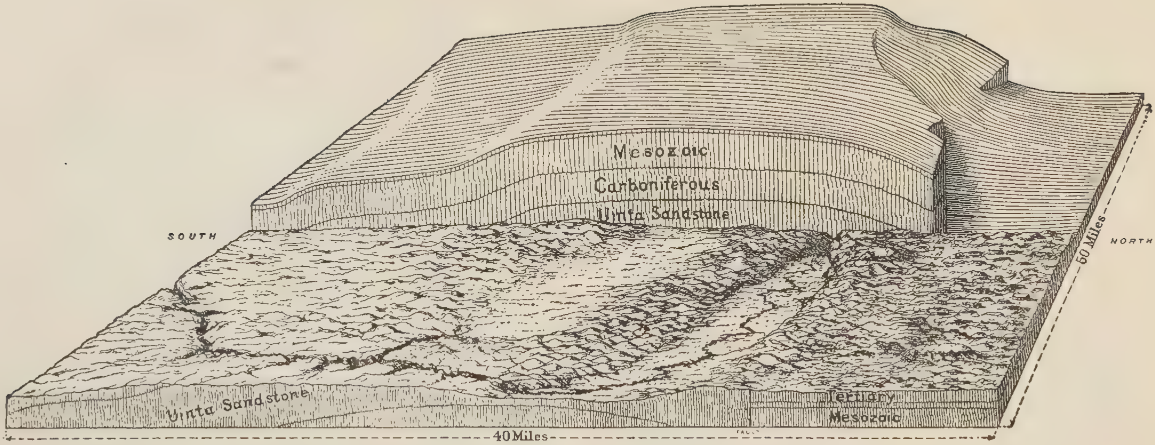

Fig. 44.—Bird's-eye view of the Uinta mountains, illustrating the relation of normal faults to broad uplifts. (After Powell.)

The block in the foreground exhibits the present surface; the block in the background is represented as it would stand had there been no degradation. The fault shown in the foreground is a continuation of the fault shown in the background. The course of the Green River through Brown's park and the Canyon of Codorie is seen in the front block. The summit of the restored block is the last bed laid down before the inception of the upheaval.

The vertical and horizontal scales are the same.

ticular fault. The maximum displacement may have occurred near one end or toward the middle of the length of the fault. At the zero point the fault ceases to exist and may pass into a monoclinal flexure or into undisturbed flat strata (Fig. 44). Furthermore, beyond the zero point the displacement may reappear with the apparent downthrow on the same or even on the opposite side of the fracture. Thus, if a fault trends north and south and the downthrow in one section is the eastern block, the movement beyond an interval of no displacement may be, in the same sense, downthrown to the east or may be, in the opposite sense, downthrown to the west. Dutton describes cases of this latter type, where the fault continues but with reversed displacement, in the Sevier and Thousand Lake faults of the High Plateaus.[1] The effect of the movements in such a case is the same as if the two blocks on either side of the fracture had rotated in opposite directions around an axis which crosses the line of the fault at the point of zero displacement.

The high-angle faults of the High Plateaus are nearly vertical, but in general the hade is to the downthrow and they are for that reason regarded as normal faults. They may, however, be due to subsidence of the downthrown block or to uplift of the raised block or to both movements. The last is the more reasonable hypothesis. The fact that the old erosion surface of the plateaus is now elevated and is cut by deep canyons demonstrates that it has been pushed up. Any section pushed higher than the one adjacent to it is upthrust with reference to that other. But also any section held back by gravity or depressed by sliding back is thrown down with reference to the upthrust section. Theoretically, the displacement may be regarded as due predominantly either to an upthrusting force or to gravity. The effect remains that of a normal fault.

Sierra Nevada Type.—High-angle faults in upthrust mountain blocks are frequently associated with rotation of the block and occur in series in such a manner that they form what are called step faults. The Sierra Nevada, California, affords a case in point.

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[1] DUTTON, C. E., Geology of the High Plateaus. U. S. Geographic and Geologic Survey of the Rocky Mountain Region, Chap. II, pp. 31 and 33.

It is a mountain mass about 600 miles long and 75 miles across. Its eastern margin carries the summits which are surviving heights on a mature landscape surface and which have also been raised to greater altitudes than any other portion of the block. The entire mountain block has been thrust up, but unequally, so that it has been rotated as though on a curved base. The mass has been distorted internally and exhibits the effects in the arching and warping of the old landscape surface. The two slopes have dragged down and are faulted. Where the range is highest the eastern slope descends from the crest in a warped surface of curved cross-section for between 2,000 and 3,000 feet. It is then faulted in a succession of normal faults, by which it drops 5,000 feet to Owens valley. The faults are very numerous and the resulting slope lies at an angle of only 28 degrees from the horizontal, yet it looks like a wall. The long western slope is also step-faulted, but not so closely nor so conspicuously. The structure is suggested by the diagrammatic cross-section shown in Fig. 45.

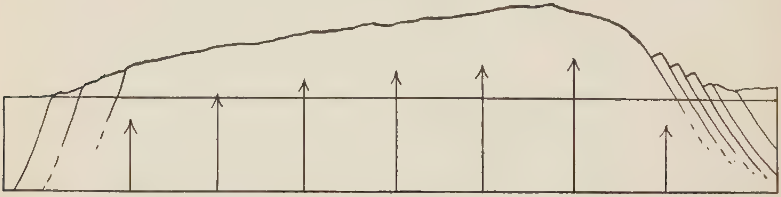

Fig. 45. Vertical upthrust caused by deep-seated compression. Diagrammatic section of the Sierra Nevada, California. Vertical upthrust accompanied by warping of the surface and normal faulting on the slopes as a result of unequal displacement upward and consequent superficial tension. Vertical scale about three times horizontal.

HIGH-ANGLE NORMAL FAULTS IN SUNKEN REGIONS

The type of fault which is common in regions where the rock-masses have sunk down in response to gravity is of the kind usually indicated by the term normal fault. It is, however, better distinguished by the name gravity fault, since normal faults may also result from upthrusts, as we have seen.

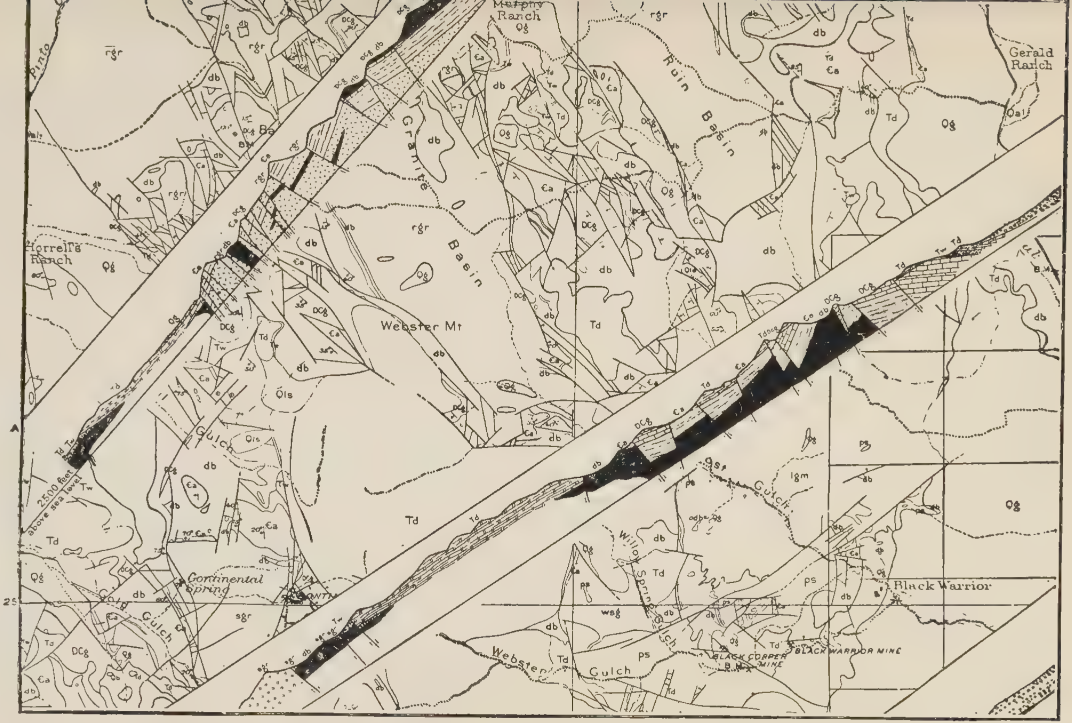

FIG. 46.—Faulting in the Globe District, Arizona. (After Ransome.) Illustrating the type of normal faulting, characteristically developed in regions of volcanic activity marked by the extrusion of lava flows.

Subsidence of any part of the earth's crust requires that the foundation shall give way, and this happens on a large scale in a manner to produce faulting chiefly through the movement of molten rock.

Faulting in Eruptive Fields.—The Globe district, Arizona, described by Ransome,[1] presents an example of complex faulting of the gravity type (Fig. 46), presumably due to intrusion and extrusion of lavas.

The rocks of the Globe region comprise both sediments and igneous rocks, and they range in age from exceedingly ancient (pre-Cambrian) formations to the most recent continental deposits. The igneous rocks occur as intrusives in the pre-Cambrian and Paleozoic sediments and also as extrusives of Tertiary and Quaternary age. That is to say, the region has repeatedly been invaded by molten rock, which has risen toward the surface and in some cases at least has flowed out over it, leaving the superficial crust unsupported. The latest occurrence of this kind is very recent.

Faulting has resulted. It is very irregular in strike and dip, as this type usually is. Ransome distinguishes two groups, those having a generally northeast-southwest trend and those striking approximately northwest and southeast. The dips may be to either side of the strikes and range from 50 to 90 degrees with a tendency to approach 75 degrees. Faults belonging to these two systems are the more conspicuous, but they are associated with

> countless other fissures running in all directions and adding greatly to the complexity of the fault network. It has proved impossible to reduce these generally subordinate fractures to distinct groups or systems. The region has not been dissected with mathematical precision along determined lines, but has been shattered by complex geological forces to an extent that is only less difficult of analysis than is a pane of shivered glass.

The principal displacements occurred after certain eruptions of dacitic lava during the Tertiary. They are normal faults, so far as their character can be determined, and there is a conspicuous absence of folding or thrusting. While it is impossible to quote as fully as one would like from Ransome's detailed description, the following may be taken from his explanatory statement, since it is probable that it is the correct interpretation of the causes of faulting in many other volcanic regions:

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[1] Ransome, F. L. U. S. Geol. Surv. Geologic Atlas of the United States. Folio 111, Globe, Arizona, pp. 11–12 and maps, 1904.

> The faulting of the Globe region is most satisfactorily accounted for by supposing stresses acting in directions more nearly vertical than horizontal, such as would result from differential elevations or subsidences over the area. . . . The causes are deep-seated and inscrutable. It is suggestive that here, as in the San Juan region of Colorado, the later fissuring followed or was correlated with an extensive transfer of volcanic material from its subterranean source to the surface. It is probable that there is a more direct connection between such volcanic paroxysms and the subsequent fissuring. The earlier, structurally less conspicuous, but economically more important, post-diabase dislocations were also preceded by great eruptive activity, and it is reasonable to regard this faulting also as a phase of regional readjustment after the widespread disturbances effected by the intrusion of the diabase.

Although it is true that the faulting of the Globe, as of similar districts, cannot be reduced to order by any mechanical analysis, it must not be assumed that the fractures follow no law. Unequal elevations and subsidences produce torsion and torsion results in systematic fractures in rigid, elastic bodies like rocks. If we could know all the conditions the phenomena would be found to be the results of reactions according to law, and in specific, limited areas, such as an individual mine may embrace, the system might advantageously be worked out. The common association of normal faults of this character with volcanic eruptions, which are also related to mineral deposits, gives to the fault type a peculiar economic interest.

Normal gravity faulting in the Globe district is probably surpassed in magnitude of displacement in regions where even larger outflows of magma have afforded opportunity for greater subsidences.

The most remarkable example of igneous outflows of various kinds on an enormous scale and of the corresponding subsidences is found in the plateaus of the Transvaal, South Africa, where the Bushveld complex was developed. The complex, consisting chiefly of norite and granite, is about 300 miles from east to west and 125 miles from north to south. The igneous rocks are remarkably sheeted and dip toward the middle from all sides, thus forming a structural basin whose actual depth cannot be determined but is very great. The floor of the basin appears to be a peneplain eroded across Archean rocks, and a reconstruction of the basin according to the observed dips indicates that it may have sunk down and been buried by eruptions to a depth of possibly 20 miles. Normal faulting must have been a prominent feature of the structures thus produced.

The subsidence of a fractured crust in consequence of outflow of lava can result in an actual basin only in case some of the magma is erupted around the margins and comes to rest outside of the original hearth. Where this is the case a defect of mass results and the surface of the sunken crust may form a hollow. This appears to have been the fact in the development of the Bushveld complex at several stages in its history, and the hollow thus formed was miles deep but filled with sediment and igneous flows.[1] The phenomena suggest a close analogy with the deeps beneath ocean basins and indicate that they also may be attributed to the escape of lava beyond their areas.

Fault Troughs or Graben.—In various parts of the earth's surface there are long narrow depressions that are bounded on both sides by faults. They have been called *fault troughs* by Sollas [2] and the term is here adopted to designate them without any implication of the nature of the faulting, whether in response to gravity or by upthrust.

A non-committal term is needed, in view of the fact that the origin of these features is often obscure and has come to be a subject of controversy. The discussion first arose in connection with that section of the Rhine valley which lies between the plateau of the Schwarzwald in southern Germany and that of the Vosges in eastern France. It is 170 miles long, the valley is broad, the fall of the river very slight, and the environment favorable for the development of commerce and industry. It is a region to which much attention has been drawn, and it has become a classic example of the type of structure which it represents. It is commonly known as the *Rheingraben*, the term *graben* having been introduced by Suess[1] to designate a sunken block. Fault trough is a translation of graben. Another English equivalent for the same geographic feature is *rift valley*.

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[1] Du Toit, Alex. L., "Geology of South Africa." Pp. 141–152, 1926.

[2] Sollas, Hertha, B. C. "Face of the Earth," vol. 1, p. 126, 1904. Translation of "Das Antlitz der Erde" by Edouard Suess.

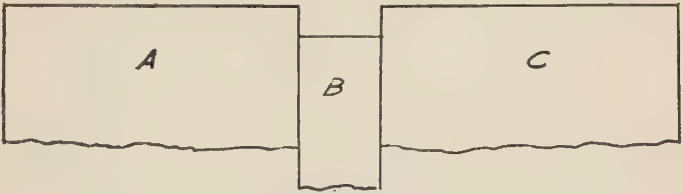

Fig. 47.—Diagram of a rift valley.

"A Rift valley is a valley produced by the subsidence of a strip bounded by two parallel faults" (Gregory). In the absence of a datum plane, the alternative of subsidence of *B*, or uplift of *A* and *C*, or displacement of all three is indeterminate.

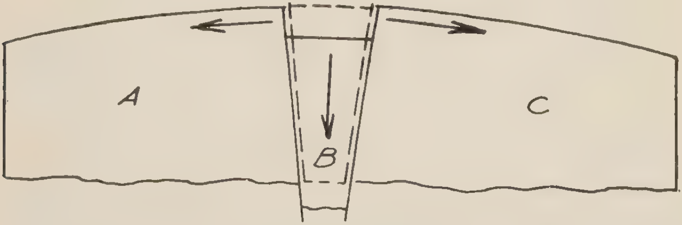

Fig. 48.—Diagram of the keystone hypothesis.

The keystone hypothesis: In consequence of the uparching of the surface, tension has developed and the keystone has dropped in.

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[1] Suess, Edouard, "Das Antlitz der Erde." Band I, Seite 166, 1892.

The different conditions to which fault troughs may be ascribed are indicated in Figs. 47, 48, 49, and 50. The first of these figures, Fig. 47, merely presents the geometrical relations which may have resulted from any one of three displacements; namely:

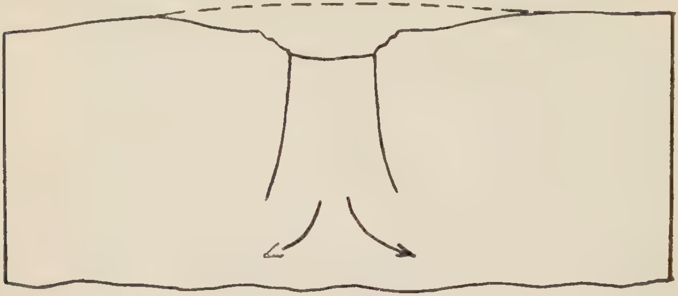

Fig. 49.—Rift idea.

Uparching relieved pressure; relief of pressure resulted in melting; outflow of melt was followed by subsidence.

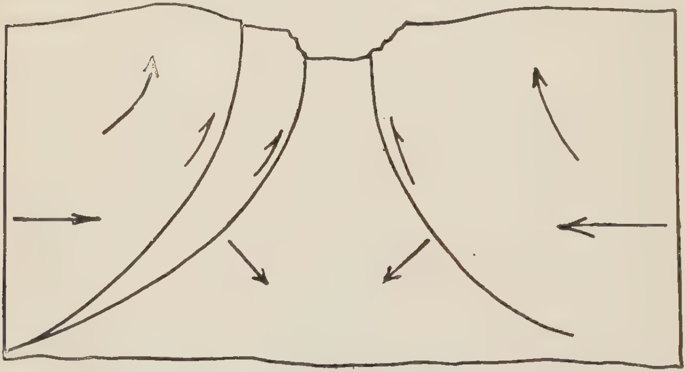

Fig. 50.—Ramp idea.

Horizontal compression resulted in the development of ramps on which the lateral blocks rode up. The swelling of the surface is due to the same forces. Components directed downward forced the keel down elastically and actually. Pressure and shearing produced melting, and subsidence was in part due to the escape of the melt.

1. Blocks *A* and *B* may have remained stationary while *C* sank down; or

2. Blocks *A* and *B* may have been raised while *C* stood still; or

3. All three blocks may have shared in their relative displacement, while the three may have been elevated or depressed as a whole with reference to their surroundings.

If the first of these displacements has occurred space must have been made under *C* in order that it should sink in. Any condition that resulted in the melting of the rock under *C* and its escape to one side or another would provide the space and might result in the sinking of *C*. (Fig. 48.) Gravity is the only force required. This is the simplest possible explanation of a fault trough or rift valley, provided that the condition of melting be given. Where rift valleys are associated with volcanos the relations are strongly suggestive.

A modification of the first case is shown in Fig. 49. The initial assumption is that the whole region has been arched up until tension produced such elongation of the arc that a keystone block sank in. It also has been used to explain rift valleys, but is open to objection on the ground of difficulty in explaining the uparching of the whole and the subsequent subsidence of a segment. It seems necessary to assume the intrusion of magma below the arch and its later escape to meet the mechanical contradictions which otherwise present themselves.

Referring again to Fig. 48 it is evident that theoretically *C* may be held fixed while *A* and *B* are being pushed up, but it is difficult to conceive of any simple vertical force that would so act as to produce the assumed displacements. On the other hand, the effect follows directly from the action of pressure, in a horizontal sense, provided that the foundations of *C* do not yield under the weight of *A* and *B* and the downward directed components of *C*. The whole system of stresses that would be developed in such a structure is shown in Fig. 50. The initial pressures are assumed to have been directed horizontally and in opposition, so that the deeper zone in which the opposed arrows are drawn was strongly compressed. The resulting shearing surfaces are curved upward toward the surface of least resistance, as the laws of shearing demand, and the displacements are supposed to occur chiefly in the same direction. Depression of the central, inverted keel-shaped block *C* would be expected, especially if lava were pressed out from under it. In more complex structures, where the block *C* may be one of many into which the foundations of the whole region are divided, it may happen that *C* would be forced down, rotated, and underthrust in the general movements. Depressions in the California Coast ranges, where great thicknesses of marine sediments have gathered in fault troughs, and similar, deeply filled valleys of the Basin ranges of Nevada and California may have been produced in this manner. Such movements might be independent of the outflow of lavas or connected with them.

Natural examples of fault troughs are probably of much more general occurrence in regions where faulting is the dominant structure than has been recognized, but there are certain great examples which have been the subject of diverse speculations, are well represented in the literature, and serve to illustrate the major facts. Brief accounts of some of them follow. Many references to these and other cases have been brought together and interpreted by Taber.[1]

A sunken wedge is described by Noble as part of a mass of pre-Cambrian strata exposed in the depths of the Grand Canyon (Fig. 51). It is part of a greatly faulted block which was displaced in pre-Cambrian time and which consists of minor

> blocks and wedges of all sizes, ranging from those included between the larger faults down to those formed by the innumerable faults of small throw. . . . 'Every detail of the wedge is revealed from its summit, where it is truncated by the pre-Tonto unconformity, down to its apex, a vertical distance of 1,000 feet. Where the fault planes traverse the harder strata they are characterized by fault breccia and slickensided surfaces.[2]

The crushing indicated by the breccia and slickensides appears

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[1] TABER, STEPHEN, Fault Troughs., *Journal of Geology*, vol. XXXV, pp. 577–606, 1927.

[2] NOBLE, L. F., The Shinumo Quadrangle, Grand Canyon District, Arizona, U. S. Geol. Surv. *Bull.* 549, p. 77 and plate 25B, 1914.

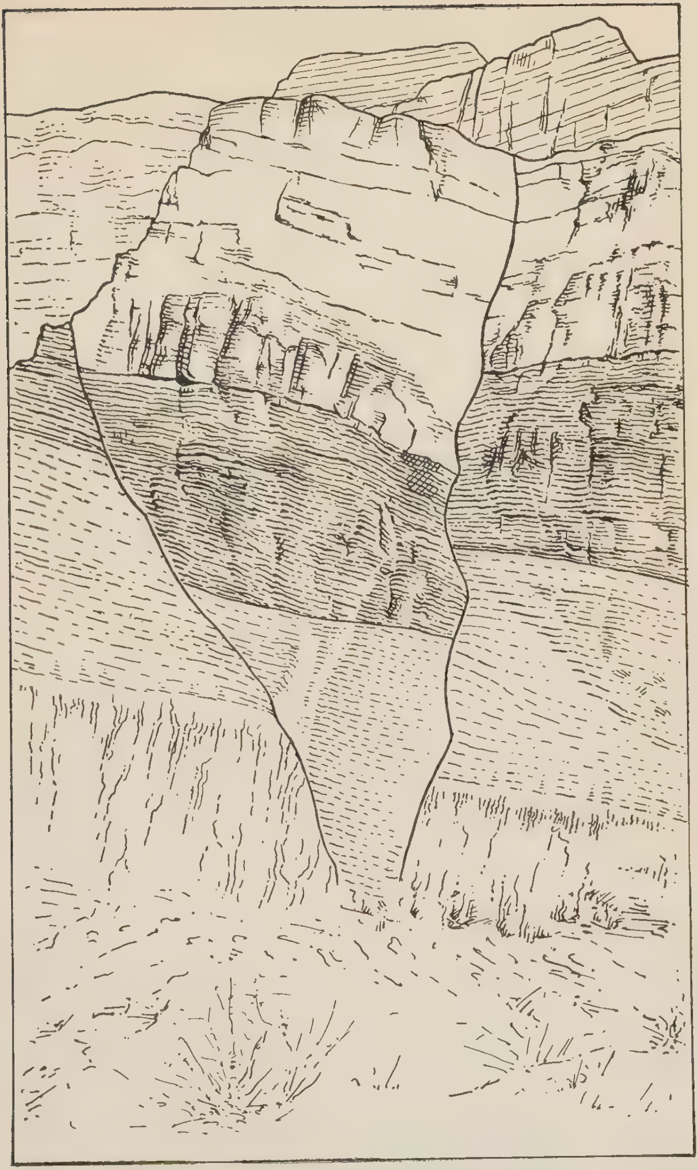

Fig. 51.—Faults in the Unkar Wedge in the Canyon of Shinumo Creek, Grand Canyon of Arizona. The wedge outline is 1,000 feet from bottom to top. Drawn from photograph. (After Noble in U. S. Geological Survey *Bull.* 549.)

to be developed on a scale greater than can reasonably be attributed to the sinking down of the wedge under its own weight. If we attribute the effects to vertical displacement we must assume that the movement involved much larger masses, whose superincumbent weight bore upon this block and its surroundings. This was probably the case. It is wise, however, to bear in mind that the displacement may have had a horizontal component of greater or less proportion, and the dropping of the wedge may be one result of local widening of the fault fissure due to horizontal displacement parallel to the fault strike, under general compressive strain.

The classic example of the Rheingraben has been described in great detail by German geologists, and the structure has been discussed by various authorities as being a result of gravitative sinking. We quote first from Suess.[1]

> *The Horsts*
>
> We will descend from the Schwarzwald into the valley of the Rhine. Here many years ago Elie de Beaumont pointed out the existence of a number of faults, which strike fairly parallel to one another towards the north-north-east, and divide into longitudinal strips the two slopes of the Schwarzwald and the Vosges which face the Rhine. According to de Beaumont there first occurred an upward dome-like swelling of the whole country, including the Vosges and the Schwarzwald, and this was followed by a step-like subsidence on both sides which formed the present Rhine valley.

The views of de Beaumont correspond in a way with the case shown in Fig. 49. Suess dissents from it, as is logical in view of his conviction that masses of the earth's crust could not be raised against gravity, and proposes instead the interpretation consistent with his ideas, namely:

> There can be no doubt that around the mountains (giving their local names) the sheets of Mesozoic deposits have sunk down, and out of

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[1] SUESS, EDOUARD., "The Face of the Earth" (English translation). Vol. I, pp. 201 et seq., 1904.

this general subsidence these mountains rise as horsts, themselves mere fragments of ancient folded chains.

We need here to make clear the view that Suess held, which was that elevated portions of the earth's crust in any region must be assumed to have remained fixed upon firm foundations while the adjacent sections subsided. He explained all displacements of a vertical attitude as effects of gravity only. His idea is diagrammatically represented in Fig. 48, and the eruptions of lava which might permit the central block to sink are not wanting in connection with the Rheingraben. But he and German geologists of the older school in general disregarded the clear evidence of uplift of the mountains or rather plateaus of central Europe, which is to be seen in the physiography. The gorge of the Rhine below the Graben is a young canyon eroded in a rising block, and there are many other features of a similar character in the adjacent elevations.

Andreae[1] (1887) and Salomon[2] (1903) describe the faults of the Rheingraben as being inclined outwards; that is, as dipping west along the western margin of the trough and as dipping east along the eastern margin, and Salomon shows that a borehole which he examined at Eberbach in Odenwald and which passed through a fault went down first into Triassic and then into Cretaceous strata. That is, the older formation is overthrust upon the younger. Deep borings undertaken near Heidelberg have in the last few years yielded additional information regarding the faults along the eastern margin of the Graben. One of these has been studied by Salomon,[3] who determined that at a depth of 3,047 feet (928 meters), the hole passed through a fault between overlying Triassic (Buntersandstein) and underlying Oligocene. This evidence he regards conclusively as indicating an overthrust, probably from the east. The particular fault reached by the drill is only one of several which are known to occur between it and the main marginal fault along the eastern side of the Graben. Their attitude is not known. Compression is, however, the obvious cause of the actual Pliocene or post-Pliocene displacements. Salomon recognized an earlier (Oligocene) development of faulting, to which he ascribed the origin of the Graben and which he, on theoretical grounds, regarded as probably an effect of tension ("Zerrung"). The inference appears to be theoretical while the evidence of the contrary effect is observational.

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[1] Andreae, A., Eine theoretische Reflexion ueber die Richtung der Rheintalspalten. etc. Verh. d. naturhistor. mediz. Vereines zu Heidelberg; N. F. IV, S. 16–24. Also S. 47–55, 1887.

[2] Salomon, Wilhelm, Ueber die Stellung der Randspalten des Eberbacher und des Rheintalgrabens. Zeitschr. der deutschen geologischen Gesellschaft, Bd. 55, S. 403, 1903.

[3] Salomon, W., Die Erbohrung der Heidelberger Radium. Sol-Therme und ihre geologischen Verhältnisse. Abhandlung der Heidelberger Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Klasse; 14 Abhandlung, pp. 1–105, 1927.

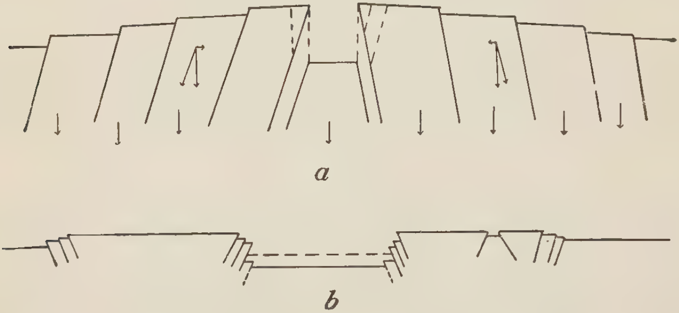

Fig. 52.—Interpretations of the Rheingraben: (*a*) lateral, horizontal tension theory of Andreae (1887); (*b*) horizontal compression theory of Salomon (1903), with depression of the central wedge, but without elevation of the lateral plateaus.

The interpretation by Andreae did not recognize these faults as effects of horizontal compression. Both he and Salomon were dominated by the idea that gravity is the dominant force, and they originated two quite different explanations to fit the theory of a shrinking earth. Andreae took account of two large basins, one to the east and the other to the west of the plateaus that in turn lie east and west of the Graben, and he argued that, as subsidence progressed in the basins, a state of tension was established in the broad strip between them. The tension developed from each basin toward the middle of the intervening plateau strip and caused normal faulting on both sides of the central line. (Fig. 52*a*.) The subsidence of the central strip, corresponding to the actual Graben, ultimately resulted. We quote Andreae's explanation of the final step:

> In the accompanying diagram it is assumed that the faults of the system are normal, as they have been observed to be in many similar cases and as is suggested by the theory. This great fault system advanced in the course of time toward the middle line as the constantly growing stress and increasing tension produced new faults. The two fault series would eventually have met in the middle of the block if, before that could happen, a point had not been reached at which the faults, spreading downward, cut out a block of triangular cross-section (R of the figure). A downward pull was exerted on its broad bottom, while its long and narrow surface, which was pinched between the thin side blocks, was not sufficiently supported. There being nothing to prevent, it broke in, often to depths of 2,000 meters.

In order to follow this reasoning it is essential to understand that Andreae accepted the idea of a contracting globe within a rigid shell, and that any portion of the shell which remained elevated would, so to speak, hang up until it collapsed.

Salomon agreed with Andreae that the faults of the Graben diverge downward and outward, but he argued that they were effects of horizontal compression. Nevertheless, he did not recognize that the sides of the Graben had been pushed up. He regarded them as immovable " horsts " which could not be elevated, and he reasoned that the intervening strips had been pressed down into the earth. (Fig. 52*b*.)

Walther deduces the earlier history of the region in which the Rheingraben occurs from the sedimentary record. It appears that Jurassic limestone was deposited over the whole area, which was therefore flat and submerged during that age; but Cretaceous strata are lacking. Hence he infers that a broad upwarp had developed and had formed a land area which continued to rise until the early Oligocene, when the first deposits were laid down in the Graben and it had begun to sink. He attributes the Graben to fracture of the rising upwarp and states the idea as follows:[1]

> The lateral pressure pressed the broad arch once more together and long fractures developed along the crest. They run in general from north to south, although they branch and cut across each other in many directions; and they extend from Belfort to Bingen, from Basel to Darmstadt and beyond across Hanau to Kassel and Göttingen. Throughout this whole stretch the earth's crust was divided into innumerable strips and triangles, and the fractures dipped downward into the depths at such diverse angles that they formed all sorts of steep planes, on which adjacent sections were either pressed down into the depths or pushed up to greater heights.

Walther also describes the associated vulcanism in the following terms:

> During the upper Miocene the sunken Graben was the scene of volcanic eruptions. The glowing hearths were opened especially in the north between Darmstadt and Kassel. Adjacent to the numerous basalt flows that occur between Frankfurt and Hanau there was built up the giant volcano of the Vogelberg and the Hessian basalt cones. In the south there is another great volcano, the Kaiserstuhl, while a number of smaller eruptions of basalt and volcanic tuff fill the marginal fissures and even extend into the neighboring horst. . . .
>
> That the tectonic disturbances which forced the Vogesen and Schwarzwald, the Hardt and Odenwald to rise alongside the strip that sank between them have not yet ceased is demonstrated by the earthquakes that are not infrequently experienced here.

Walther thus advanced beyond the view of Suess in that he recognized the fact that the horsts had been pushed up, even while the graben were being pressed down. He does not, however, refer to the physiographic evidence of uplift, which is so obvious to the later student trained in that kind of observation.

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[1] Walther, Johannes, "Lehrbuch der Geologie von Deutschland," p. 183, 1910.

Ibid. Über tektonische Drückspalten und Zugspalten. Zeitschrift der deutschen geologischen Gesellschaft, Band 66, Monatsberichte, pp. 284–311, 1914. Page 303 "Die Hörste."

The antecedent course of the Rhine, which is now deeply incised in the plateau from Bingen to Koblentz, admits of no other explanation than that the mass of the plateau has been raised at a rate which permitted the river to maintain its channel. This evidence is mentioned by Kober,[1] who sums up the modern German understanding of these structures, graben and horsts, as follows:

> As is indicated by the terms (graben and horst) we have to deal with a portion of the earth's crust which is characterized by division into strips and blocks that have been displaced with reference to one another. Some are pressed down into the earth, others are raised up. The sunken blocks correspond with the graben, the elevated ones are the horsts. Normal faults and thrusts develop and volcanic phenomena often occur. In consequence of the inequalities developed by the graben and horsts a new morphological aspect is produced. Erosion is stimulated by the upwarping of the blocks. A new geographical cycle is initiated. . . . Where formerly there may have been a broad plain, an old-age landscape, there now develops a youthful stage as result of the dislocations. . . . The differences of relief may be considerable. On the summits of the horsts the old landscape may long remain recognizable. . . . A well-known example of that which has thus been described is furnished by the Rheingraben, with the horsts of the Schwarzwald and the Vogesen.

Application of the methods of elementary physiographic analysis to the study of structural problems, although well established in American practice, was at the time Kober wrote relatively new in Europe, and his description of it is therefore the more significant. We give below the section of the Rheingraben illustrated in his work, the faults being shown as converging downward, and also an adaptation of their downward extension that better suits the idea of lateral compression, the faults being curved outward. (Fig. 53.)

From these descriptions of the Rheingraben we may gather that the plateaus have been upthrust, the Graben has been downthrust, and considerable volumes of lava have been extruded from a deep-seated source during the more active stages of the process of dislocation. There is evidence of an initial doming of the area before the fractures developed, and the latter are attributed to the superficial splitting of the arch along its axis. This last deduction is a step in hypothesis which is open to question, because the phenomena of uparching, tension, and collapse are inconsistent with those of compression, shearing, upthrusting and downthrusting.

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[1] Kober, Leopold, "Der Bau der Erde," page 50, 1921.

In Palestine, Arabia, and eastern Africa there are trough faults of remarkable extent, comprising the Jordan valley, the Dead Sea and Gulf of Akaba, the Red Sea, and the great " Rift valley " of eastern Africa. The Jordan-Akaba depression, as it may be called from its two extremities, is the best known and possibly the most remarkable trough in the world. It is 400 miles long, from its head where the waters of the Jordan gather to form the main river to Cape Ras Mohammed where it enters the Red Sea. It is 15 to 20 miles wide between plateau margins, and in the deepest part it

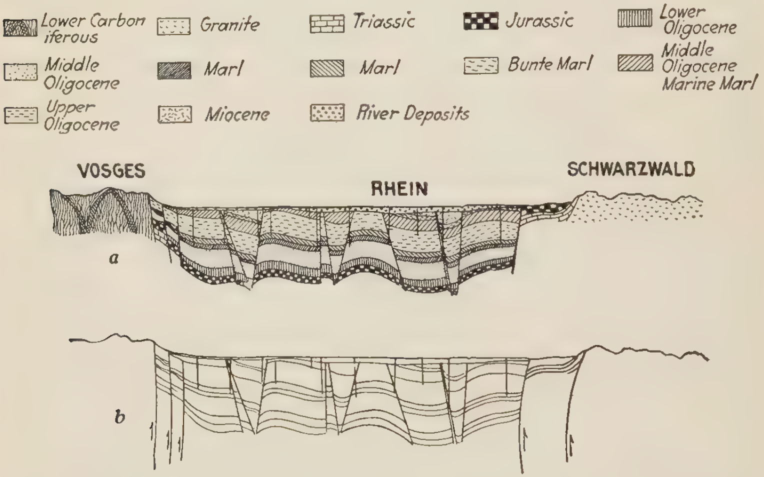

FIG. 53.—*a*. Profile through the Middle Rhine Valley to the north of Muhlhausen in Alsace. The structure of the low-lying Rhine-valley block between the Vosges and the Schwarzwald, from borings. The strata in general belong to the Middle Oligocene and later periods, lying on the Upper Dogger. (From Tornquist, "Formationskunde," elaborated by W. Wagner. After Kober, "Der Bau der Erde," 1921.) *b*. The same, as interpreted if due to compression.

descends to 2,600 feet below the Mediterranean. The level of the water of the Dead Sea is 1,292 feet below the Mediterranean, and the water is 1,308 feet at the deepest sounding. Referred to the plateaus on either side the bottom of the trough reaches a maximum of 5,193 feet below Jerusalem and 5,243 below Mt. Nebo. It thus lies like a sunken keystone between two elevated arches of equal height. The suggestion that it is due to the apparent sinking in of the keystone is very obvious, but opinion is by no means agreed that such is the case, and there is much evidence to indicate that even this great depression may be an effect of the forces of compression from which the associated structures evidently resulted.

The Dead Sea trough is a true fault trough in the sense that it is undoubtedly bounded on both sides by faults and they are essentially parallel. The faulting has been recognized by all geologists who have examined the region since the earliest decades of the nineteenth century, and until quite recently there has been little question of their being normal faults. Lartet [1] (1877), Hull [2] (1886) and Blanckenhorn [3] (1896 and 1914) have upheld this view after personal explorations of the region. Bailey Willis [4] (1927) reached the conclusion that the plateaus which bound the Dead Sea trough have been thrust up on either side of it. In order to distinguish the type of curved upthrust faults on which the plateaus are thought to have been pushed up he designated them by the term *ramp*, which he placed in opposition to rift, the name given by Gregory to normal faults in similar positions.

The stress conditions that distinguish rifts and ramps are shown

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[1] Lartet, L. M. H., "Exploration geologique de la Mer Morte et de l'Idumée." Paris, 1877.

[2] Hull, Edward, "The Survey of western Palestine with special reference to the mode of the formation of the Jordan-Akaba depression and the Dead Sea," 1886.

[3] Blanckenhorn, M., Syrien, Arabien, und Mesopotamien. *Handbuch* der reg. Geol. Heidelberg, 1914.

Ibid. Entstehung und Geschichte des Toten Meeres. Zeitschr. D. Deutsch. Palaestine-Vereins xix, 1896.

[4] Willis, Bailey. The Dead Sea Problem, Rift Valley or Ramp Valley. *Bull.* Geol. Soc. Am., vol. 39, pp. 490 to 542, 1928.

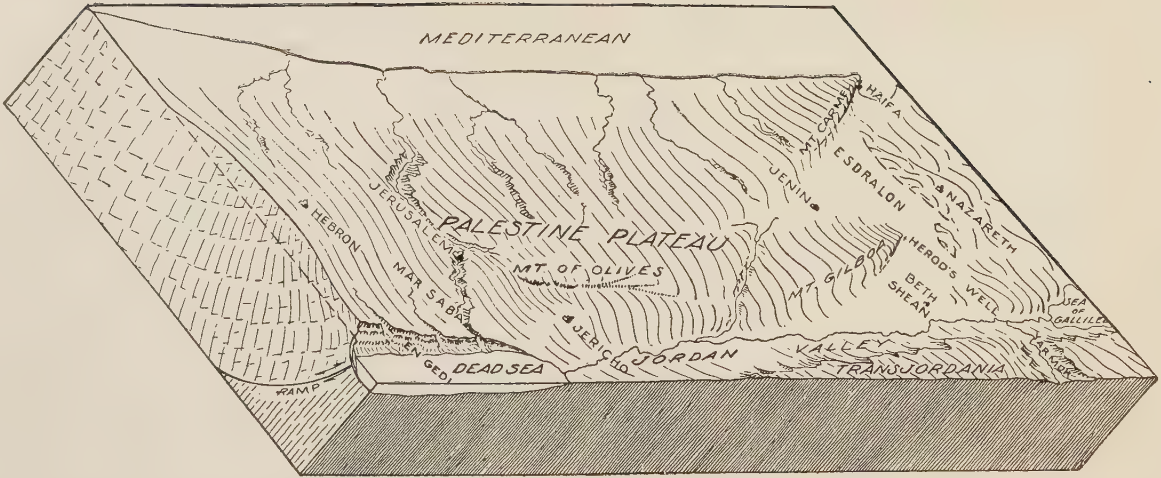

FIG. 54.—Block diagram of the Palestine Plateau and Dead Sea. Showing the actual surface relief in a generalized form and the major ramp on which the plateau has been raised, according to the view developed in studying the structural facts in the field. (Bailey Willis).

in Figs. (49) and (50). The ramp that is supposed to underlie the Palestine plateau is delineated in the block diagram, Fig. 54. Definitions of a rift and ramp are as follows:

Rift: Displacement due to gravitative subsidence (Gregory, J. W., Great African Rift valley).

Ramp: (new term). Upthrust, a compression fault, connoting a high-angle attitude in part at least; the opposite of *rift*.

These ideas being defined, we may place the hypotheses which they represent in parallel statement for convenient comparison, as follows:

FUNDAMENTAL CONCEPTS; RIFT VERSUS RAMP

Rift

It is assumed that a segment of the earth's crust has been arched up. The conditions of the arching may be discussed as involving either compression by tangential forces or vertical forces acting directly upward. The elongation of the segment due to arching results in tension, which is a condition favorable to normal faulting. Faulting ensues and a strip sinks in between parallel faults. The effect is to produce a rift valley.

It is observed that rift valleys are frequently associated with volcanic outflows. It is postulated that the uparching of the segment relieves pressure on highly heated masses and thus promotes melting. The resulting outflow of lava and consequent removal of material from under the arch is a contributory cause of the subsidence of the rift zone and the formation of the valley.

Applying these concepts to the Dead Sea trough, we recognize the initial arch in the Palestine and Transjordan plateaus, which may be conceived to

Ramp

It is postulated that tangential compression is the dominant cause of uplift and displacement of the earth's crust. It may act in a superficial layer and produce folds or flat overthrusts; or it may be exerted in a deeper seated zone and by shortening the horizontal dimension of an incompressible mass may cause it to extend upward and thus to exert a vertical force; or again, deep-seated compression may produce steeply inclined upthrusts or ramps and may force the overlying masses to rise on them.

A ramp may develop singly and produce an escarpment overlooking a lowland, or two opposed ramps may rise facing one another. In the latter case a ramp valley lies between. It is established that compression and shearing promote melting of rocks by raising the temperature, and it is reasonable to assume that melting or metamorphism accompany deep-seated displacements on ramps. The outflows of lava noted in connection

Rift	*Ramp*
have been continuous across the trough; we see the rifts as the two escarpments, and we may assume a relation between the subsidence of the Dead Sea block and the basalt flows in Transjordania.	with ramp valleys are thus accounted for. Applying these ideas to the Dead Sea trough and the adjoining plateaus, we recognize two arched uplifts, two ramps, and the depressed block. The elevations and depression are intimately related as effects of the general pressure to which the blocks have been subjected. The lava flows are closely related effects and they have been forced out by the same pressure.

The theory which postulates that the faults along a fault trough are normal gravity faults or rifts very commonly carries the corollary that an arch was stressed to the point where it failed because of tension, as was suggested by Suess and Andreae. The mechanics of a failure of this kind present difficulties where the materials to be stressed are jointed rock masses and the dimensions are as great as those of the structure under consideration. The idea does not seem workable. Moreover the tension effects would be very superficial as compared with the depth of the activities which could develop the tremendous pressures involved and the large masses of igneous magmas erupted. It is important that the magnitude of the phenomena should be grasped in order that the theoretical concepts may be commensurate with their grandeur.

There are in East Africa fault troughs which illustrate the peculiarities of the structure on a much larger scale even than that of the Dead Sea trough. They have become widely known as the great African Rift valleys, especially through the writings of Professor J. W. Gregory.[1] Gregory accepted the suggestion of

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[1] Gregory, J. W., "The Great Rift Valley," being an account of a journey to Mt. Kenya and Lake Baringo, 1896.

Ibid. The African Rift Valleys. *Geographical Journal*, 1920.

Ibid. "The Rift Valleys and Geology of East Africa and account of the origin and history of the Rift valleys of East Africa," etc., 1921.

Suess to the effect that the Rift valleys represent a dominant lineament of the globe, which extends for a distance of 4,000 miles, from Lake Nyassa in South Africa to the Jordan valley in Syria, and includes the African Rift valleys, the Red Sea depression, and the Dead Sea trough. This is one of those broad, but speculative concepts that appear reasonably probable so long as they are not embarrassed by too many facts. Suess made his suggestion on the basis of what was known of East Africa at the beginning of this century. His genius for connecting and correlating tectonic lines led him to extremes. The accumulating facts now indicate that the African Rift valleys are neither topographically continuous nor certainly attributable to identical causes, and that the Red Sea and Dead Sea are distinct structural depressions which may or may not have had similar histories. The general relations may be described as follows:[1]

Lake Victoria Nyanza, a large, rudely circular lake, approximately 200 miles in diameter, occupies the middle of a high plateau, which is assuming the form of a basin. The middle is subsiding with reference to the margins, but there is no means of observing whether the one is actually sinking or the others rising or if all are changing in level. The plateau is bounded on the east and west by very long and narrow valleys that usually have steep or precipitous sides. They constitute the Western and Eastern Rift valleys. Although they have been described as straight rifts they are in fact curved and the mass of the plateau enclosed between them is an oval, whose major axis from north to south is 850 miles long while the minor axis from east to west is 500 miles.

The Western Rift valley comprises from north to south a group of long, narrow lakes and also several volcanic piles that rise either in or closely adjacent to it. They are Lake Albert Nyanza, Volcano Ruwenzori, Lake Edward, the volcanic group Mfumbiro, Lake Kivu, and the great Lake Tanganyika. They lie in an arc of 85 degrees on a radius of 600 miles. Some idea of the magnitude of this huge structure may be derived from the following details. Lake Albert Nyanza, at the northern end of the Rift, is bounded on

[1] Consult the *London Times* Atlas, Plate 70.

the east by a precipitous face 1,000 to 1,500 feet high, while the western shore is formed by a chain of lofty mountains, the highest peaks of which rise 8,000 feet above the level of the lake. The mountain scarps are compared to walls resembling those of a Norwegian fiord. Lake Tanganyika is 420 miles long by from 20 to 40 miles wide. Its water surface lies 2,530 feet above sea level and its bottom 1,660 feet below sea level, a depth of 4,190 feet having been sounded.

The Eastern Rift is not so continuous. It has been described as extending from Lake Rudolph in the north to Lake Manyara and presumably beyond the latter toward Lake Nyassa. The line is at least 600 miles long and slightly concave toward the west. But Lake Rudolph lies far to the north, appears to occupy an independent depression which lacks the steep walls so characteristic of fault troughs, and may not belong to the structural group of the Rift valleys proper. If it be disregarded, the Eastern Rift valley may be described as curving about the central basin occupied by Lake Victoria Nyanza, about 200 miles outside of the lake, and as extending from Lake Baringo through Lake Naivasha to Lake Eyashi, that is, from northeast to southeast of the Victoria basin. The structure lies in an arc of 60 degrees on a 300-mile radius and is 350 miles long. Volcanic eruptions of large volume occur in the Rift zone and also outside of it. Among the latter are the great masses of Mts. Elgin, Kenya, and Kilimanjaro.

For convenience of discussion it is desirable to be able to refer to the group of Rift valleys, volcanic eruptions, and related structural features that surround and include the basin of Lake Victoria Nyanza by a group name, and for that purpose the term *Nyanza group* or *structure* is here introduced.

The broad depression of Lake Rudolph, lying north of the Nyanza group, is the southern feature of a chain of depressions that extends northeast across Abyssinia to the Gulf of Aden and the Red Sea. The structural character of this zone is not yet determined, but the depressions have been referred by Suess and Gregory to the great hypothetical line of rifts.

Toward the south the Nyanza group appears to be related to the great fault trough of Lake Nyanza, which extends south to the coast at the mouth of the Zambesi.

It was at one time suggested that the great Rift valleys were the effects of erosion, but there is now no question but that they are due to faulting. There are, however, differences of opinion as to whether the major faults are normal and therefore indicate tension or are reversed and express compression. Gregory is the champion of the tension theory, whereas the compression theory has recently been put forward by Wayland.[1] The accompanying diagrams (Fig. 55) are taken from the latter's paper. It is not the purpose in this description of great high-angle faults to discuss the origin of the Rift features. It may be noted, however, that the three great examples which have been cited, namely, the Valley of the Rhine, the Jordan-Akaba trough, and the great Rift Valley of Eastern Africa, are all of them similarly situated in the summits of plateaus

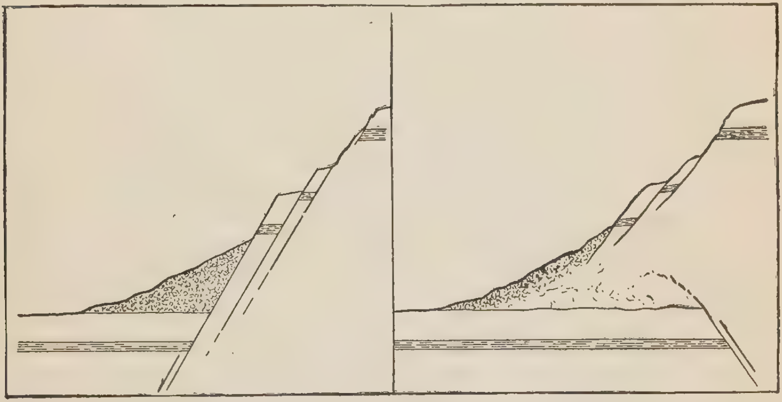

Fig. 55.—Sections of the Albert Nyanza Rift valley. (After Wayland.)

(*a*) Interpretation of the valley as a dropped block bounded by normal faults. (After Gregory.)

(*b*) Interpretation of the valley as an effect of upthrust from either side, according to Wayland, the normal faulting being a subordinate feature.

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[1] Wayland, E. J., Some Account of the Geology of the Lake Albert Rift Valley. *Geologic Jour.*, vol. LVIII, pp. 344–359, 1921.

and may be explained, either as effects of collapse after a preceding uparching of the surface, or as depressed strips which have been overridden by segments of the plateau pushed up from either side. The mere fact of the existence of a graben, bounded by steep fault scarps which exhibit normal faults equivalent to landslides, is not in itself demonstrative evidence either of tension or of compression.

LOW-ANGLE OVERTHRUSTS

The Type.—Consider Fig. 39*c*. Let it be assumed that the block *B* is regarded as having been held fixed in position and that *A* has been pushed over and upon *B*. Then the block *A* has been overthrust upon *B*, and the displacement has caused the overthrust fault which divides the blocks. The dip of the fault plane shown in the diagram is 45 degrees. If the dip were less the fault would be a low-angle overthrust of the type described in this section.

Any thrust fault which has a dip of less than 45 degrees to the horizontal is by definition a low-angle thrust. If the mass above the fault has demonstrably moved over the relatively fixed mass below the fault, then the displacement is an *overthrust.* The alternative structure is one which has a similar low dip, but which has been produced by movement of the block below the fault under the relatively fixed block above the fault. Such a displacement is called an *underthrust* and is by definition a low-angle *underthrust.* This type is described on pages 121 to 125. The following paragraphs deal with low-angle overthrusts.

Low-angle overthrusts may be produced in connection with overturned folds by the stretching of the overturned limb (Fig. 18); or they may develop as shearing planes and minor folds may result from the dragging of one block on the other (Figs. 56, 57, 58); or they may result from the forward movement of a huge wedge of the earth's crust which, being horizontally displaced, advances over the surface, in some cases for miles. (Figs. 59, 60.)

The first discovery of a thrust was made in 1826 by Weiss, a German geologist, who in the vicinity of Dresden observed that an ancient granite lay flat upon Cretaceous strata in a position which he recognized as due to an overthrust movement.[1] His explanation was, however, met with incredulity by the then masters of the science. Yet eleven years before Sir James Hall had correctly described folds produced by compression, and it seems, in the light of our present knowledge, an obvious inference that overthrusts result from the same action.

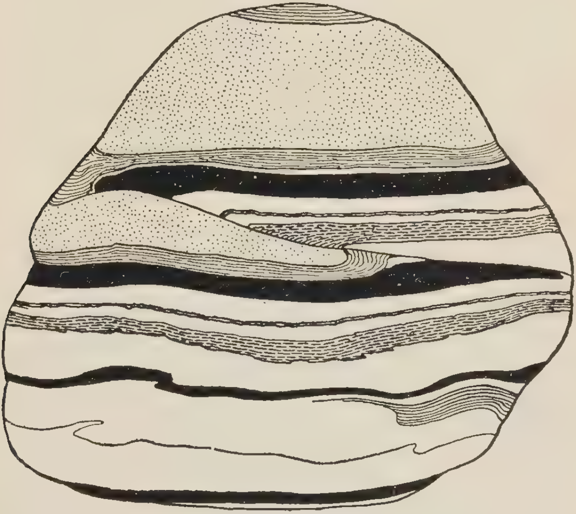

Fig. 56.—Illustration of a low-angle thrust. (Drawn from a pebble in the Stanford collection.) The bedded strata of the original rock were bent and sheared by the overthrust which traverses the middle of the pebble. The pebble was subsequently worn from a fragment of the rock, but it did not part on the thrust plane. About three times natural size.

Appalachian Thrusts.—H. D. and W. B. Rogers were the first to connect overthrusts with folds. In their investigations of the structure of the Appalachians they found that "inverted flexures frequently pass into faults," which invariably arose along the northwest side of an anticlinal axis and like the axes of the folds maintained a remarkable parallelism.[1]

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[1] Rothpletz, A., Die Ueberschiebungen und ihre methodische Erforschung. *Compt. Rend.* International Geological Congress, Zurich, p. 252, 1894.

The observations of the Rogers brothers were made chiefly in Pennsylvania and Virginia. Safford observed in Tennessee thrusts of a similar but more pronounced character, associated

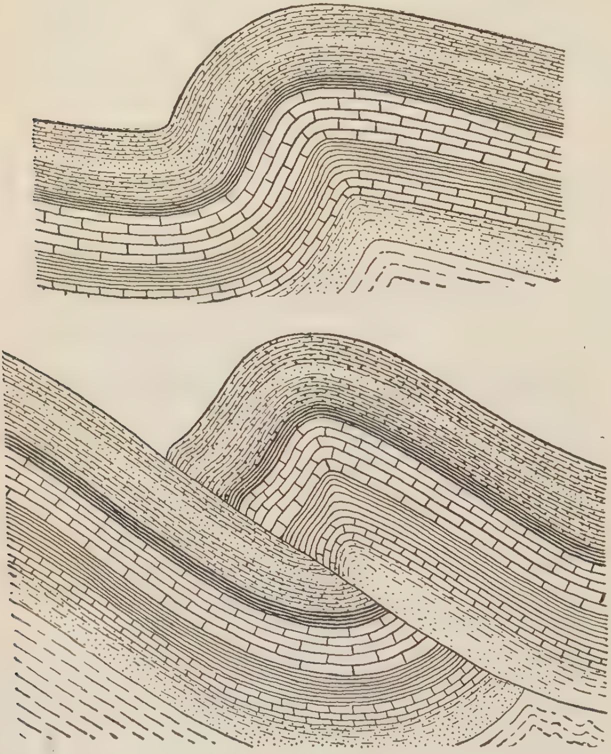

FIG. 57.—Development of a thrust of the Appalachian type, a break thrust.

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[1] ROGERS H. D. and W. B., On the Physical Structure of the Appalachian Chain, as exemplifying the laws which have regulated the elevation of great mountain chains generally. *British Assn. Reports*, vol. 12, Trans. of Sec's, pp. 40–42, 1842. *Am. Jour. Sci.*, vol. 44, 359–365, 1843.

with less developed folds. Describing a section across the most closely compressed portion of the Valley of Tennessee, he wrote:

> The length of the section is 52 miles. Eight great faults are crossed. . . . It is to be observed that no great flexures occur. . . . The incipient folds were split open longitudinally and the southeast side of each was heaved up and over the northwestern.[1]

The unequal development of folds and thrusts in the Virginia, Pennsylvania, and Tennessee sections of the Appalachian Valley was subsequently explained as a result of the difference of load resting on more or less deeply buried strata. In each section the controlling stratum was a very thick limestone, which, under less load, broke (Fig. 57) and was overthrust at an earlier stage of development of the folding than where it was more heavily loaded.[2]

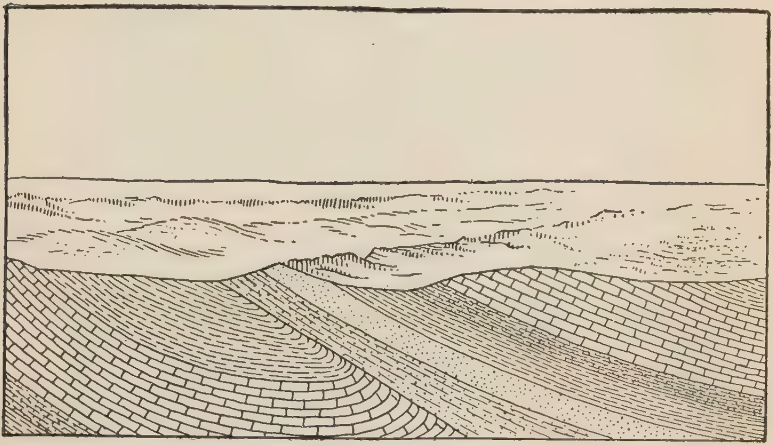

FIG. 58.—Perspective view and section of a thrust of the type common in eastern Tennessee, a variety of the Appalachian thrusts.

Two other types of low-angle overthrusts occur in the southern

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[1] SAFFORD, JAMES M., "Geology of Tennessee," pp. 189–190, 1869.

[2] WILLIS, BAILEY, Mechanics of Appalachian Structure. U. S. Geol. Surv. *Thirteenth Ann. Report*, pp. 226–230, 1890.

Appalachian ranges, both of them differing from that which has just been described in that they are not directly connected with folds. It is indeed possible that they originated in deep-seated shearing in rocks that could not fold.

In one type overthrusts, presumably originating deep beneath the zone in which strata can fold or in the zone of folding, extend to the surface and there produce remarkable conditions of superposition. Effects of this character were first observed by Russell in Georgia, in the southern extension of the Appalachian faulting, and were correctly interpreted by Hayes. The older strata (Cambrian) were found to rest, apparently without disturbance, upon younger (Carboniferous) over large areas. The Cambrian lies in synclines seemingly conformably, on an eroded surface of the Carboniferous. Hayes[1] explained this anomalous condition by

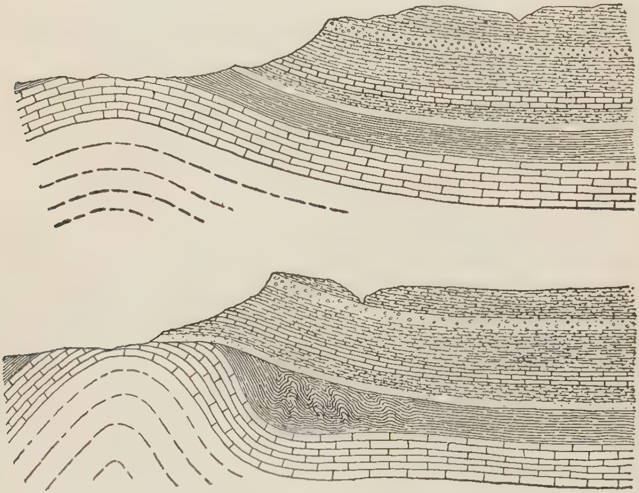

FIG. 59.—Development of an erosion thrust of the southern Appalachian type. (After Hayes.)

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[1] HAYES, C. W., Overthrust Faults of the Southern Appalachians. *Bull.* Geological Society of America, Vol. 2, pp. 141–152, 1891.

assuming that in an adjacent section erosion had removed the crest of a slight fold in such a manner as to expose the edge of a rigid stratum, and the latter, meeting with no resistance, rode forward on the eroded plain. (Fig. 59.)

Bailey Willis, following Hayes' explanation, called this kind of overthrust, which corresponds to displacement on an eroded surface, an *erosion thrust.* The name is, however, not well chosen, for the magnitude of the displacements on thrusts of this character is quite inconsistent with the superficial relations which it suggests. (See Rocky Mountain thrusts, p. 106.)

Another type of thrusts of extremely complex character is described by Keith[1] who, after years of investigation working out the complex structure of the Smoky mountains of North Carolina, found there great shear planes—overthrusts—which antedated the folding and are themselves folded in anticlines and synclines. In this case the shearing had originated in gneisses and granites deep beneath the horizon of stratified rocks and had no relation to any folds, except those which were induced in strata in the line of the displacement.

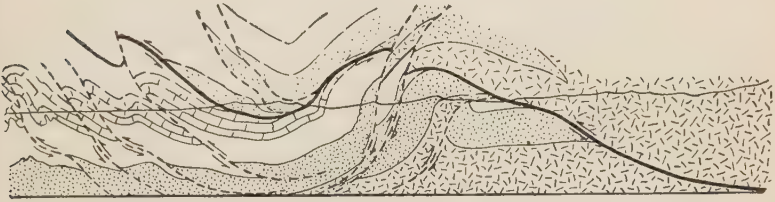

FIG. 60.—Dislocation and flexure of a major thrust (heavy line) by later minor thrusts and folding. Roan Mountain, North Carolina—after Keith—Roan Mountain folio, Geologic Atlas of the United States.

In complexity of development the thrusts that traverse the pre-Cambrian gneisses and Cambrian strata of the Smoky mountains resemble the observed structures of the Swiss Alps. (See p. 113.)

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[1] KEITH, ARTHUR, Roan Mountain Folio, U. S. Geol. Surv., Geologic Atlas, No. 151, text and structure sections.

Rocky Mountain Thrusts.—McConnell,[1] describing a section of the Rocky mountains near the fifty-first parallel, in 1886, drew a comparison between the structures he had observed in Tennessee and those of the Rockies. Regarding the latter he says:

> In the section examined there are seven principal faults, besides some of minor importance, and six well-defined blocks, the latter resting on one another in regular succession from west to east. . . . Overturned folds were observed along the course of some of the faults, but they are usually small and of minor importance as a structural feature.

The comparison of the faults observed by McConnell with those which originated in the folded strata of the Appalachian zone is not very accurate, since the former are less intimately related to overturned anticlines. They appear rather to represent the overthrusts and incidental folds which have been produced in the mountain mass that has been thrust upward and forward on a thrust plane of far deeper origin.

Examples of the thrusts attributable to pressure from deep sources are very strongly developed along the Rocky mountain front in the United States.

The Glacier National Park, Montana, from the 49th parallel southward to the Lewis range, which is there the eastern height of the Rockies, overlooks the Great Plains with a precipitous face. The mountains consist of nearly horizontal strata of a very ancient period (Algonkian) underneath which lie much younger strata (Cretaceous) that are closely folded. The contact of the older strata upon the younger is an overthrust which dips toward the west at the very low angle of 4 to 7 degrees. The thrust plane is exposed for 7 miles in the valleys cut down through the mountain mass, and it is clear that the Lewis range has been pushed that distance eastward over the surface of the Great Plains.[1]

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[1] McConnell, R. G., Report on the Geologic Structure of a portion of the Rocky Mountains. G. and N. H. Survey of Canada, *Report*, part D, p. 31, 1886.

The Lewis overthrust is comparable in superficial character with the Rome and Cartersville thrusts of the southern Appalachians (see p. 104). In the Rocky mountains it is but one of a number of more or less similar faults that occur along or near the eastern base of the ranges. They are enumerated by Mansfield,[2] who gives references[3] to the literature in which are described thirteen great overthrusts occurring between the Canadian boundary and central Wyoming, between latitudes 49 and 41. Each one has been discovered in the course of local surveys and as yet remains recognized only as an individual feature. But they may all be considered as parts of a great structure or structures, which have been developed in the northeastward movement of the masses of the Rockies.

Highland Structure.—Thrust faulting on a great scale, with or without folding but with folding a subordinate feature where it does occur, characterizes a remarkable region in the Northwest Highlands of Scotland and having been first recognized in that region has become known as " Highland Structure."

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[1] Willis, Bailey, Stratigraphy and Structure of the Lewis and Livingston Ranges, Montana. *Bull.* Geological Society of America, vol. 13, pp. 305–352, 1902.

Campbell, M. R., The Glacier National Park. U. S. Geological Survey *Bull.* 600, pl. 13, 1904.

[2] Mansfield, Geo. R., Geography, Geology, and Mineral Resources of Southeastern Idaho. U. S. Geological Survey Prof. Paper 152, 1927; pp. 379–383 for general account and map.

[3] Willis, Bailey, op. cit.

Blackwelder, E., Geology of the Wasatch Mountains, Utah. *Bull.*, G. S. A., vol. 21, pp. 517–542, 1910.

Richards, R. W., and Mansfield, G. R., The Bannock Overthrust, Idaho, *Jour. Geol.*, vol. 20, pp. 681–709, 1912.

Ziegler, V., Foothills Structure in the Rocky Mcuntains, *Jour. Geol.*, vol. 26, pp. 715–740, 1917.

Dake, C. L., The Hart Mountain Overthrust, Wyoming, *Jour. Geol.*, vol. 26, pp. 45–55, 1918.

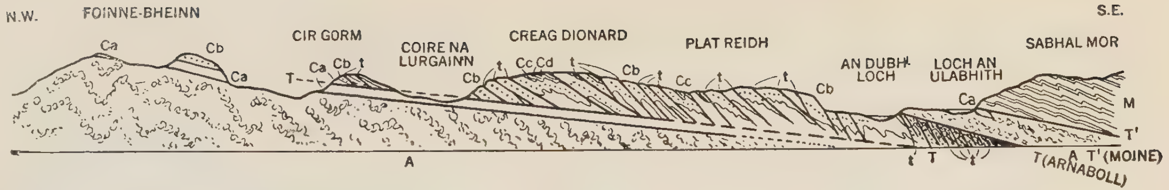

Fig. 61. Highland structure. Section from Foinne-Bheinn by the Plat Reidh and An Dubh-Loch to Sabhal Mòr, showing the basal quartzite of the Cambrian resting unconformably on the Lewisian Gneiss and itself overridden by higher members of the Cambrian series which have been pushed from S.E. to N.W. on a major thrust and piled up by successive minor thrusts. On the right of the section the Lewisian Gneiss and the Eastern Schists are shown over thrust upon the Cambrian.

A. Lewisian Gneiss. *Ca*. Basal Quartzite (Cambrian). *Cb*. Pipe-rock. *Cc*. Fucoid-beds. *Cd*. Serpulite-grit. *Ce*. Limestone. *M*. Eastern Schists. *T*. Thrusts. *T'*. Moine thrust. *t*. Minor-thrusts.

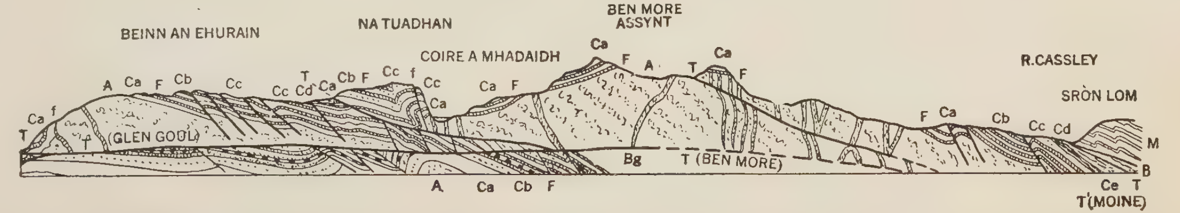

Fig. 62.—Highland Structure. Section from Beinn Gharbh by Cnoc an Droighinn, Beinn an Fhurain, and Ben More, Assynt, to the River Cassley, showing the pre-Cambrian (Lewisian) Gneiss overthrust upon the Cambrian and the latter piled up by numerous minor thrusts.

A. Lewisian Gneiss. *Bg*. Dykes in Gneiss. *B*. Torridon Sandstone. *Ca*. Basal Quartzite (Cambrian). *Cb*. Pipe-rock. *Cc*. Fucoid-beds. *Cd*. Serpulite-grits. *Ce*. Limestone. *Ce*. I. Limestone (Ghrudaidh group). *Ce*. II. Limestone (Eilean Dubh group). *F*. Intrusive Igneous Rocks. *M*. Eastern Schists. *T*. Thrusts. *T'*. Moine thrust. *f*. Faults.

The Northwest Highlands had, through the researches of many of Great Britain's foremost geologists, including Murchison, long been the scene of controversy, when Messrs. Peach and Horne made it classic ground by their penetrating and decisive investigations, which established beyond question the existence of a type of structure previously unknown and in the light of the then existing knowledge of earth-dynamics inconceivable. The history of investigation from 1814 to 1900 is summarized in Chapter 2 of the Memoir published in 1907.[1] In the course of the many and detailed studies of the rocks and their succession made during nearly a century the thrusts had been regarded as unconformities, and theories had been evolved to account for the metamorphism of apparently younger, overlying strata where underlying strata are not altered; the fact being that the overlying are older than the underlying, upon which they are overthrust. (Figs. 61, 62 and 63.)

Horne thus summarizes the description of the structures:[2]

> 1. By lateral compression of the earth's crust the rocks have been thrown into a series of folds, usually inverted, accompanied by several faults or thrusts. The general strike of these folds and dislocations is from N.N.E. to S.S.W. The axial planes of the folds, the reversed faults, and the component beds dip, as a rule, in one direction towards the E.S.E. In the middle limb of the overfold the constituent particles are attenuated, and along that limb, the overfold may or may not pass into a reversed fault.
>
> 2. Without incipient folding, the strata are repeated by a series of minor thrusts or reversed faults, which lie at an oblique angle to more important dislocations, termed by us major thrust planes. They are likewise inclined to the E.S.E., the direction from which the pressure proceeded.
>
> 3. By means of major thrusts of varying magnitude, striking generally N.N.E. and S.S.W., the following structures have been produced: (*a*)

---

[1] The Geological Structure of the Northwest Highlands of Scotland, by B. N. Peach, John Horne, and others, edited by Sir Archibald Geikie, *Memoirs* of the Geological Survey of Great Britain, 1907.

[2] Ibid., pp. 463–464.

certain subdivisions of the Cambrian system have been heaped up and driven westwards along planes produced in underlying undisturbed materials; (*b*) masses of Lewisian gneiss with its uncomformable covering of Torridon sandstone and Cambrian strata override the piled up strata beneath; (*c*) the Eastern schists have been thrust far to the West till, in some instances, they rest directly on undisturbed Cambrian rocks.

4. Owing to the travelling of the rocks from East to West and also to the friction along the unyielding lower plane or "sole" of the thrust, there was a tendency in the materials to fold over and curve under, thus producing inversion.

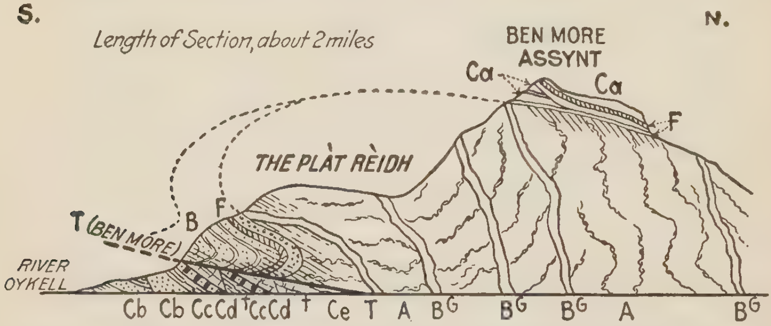
S.
N.
Length of Section, about 2 miles
BEN MORE ASSYNT
Ca
Ca
F
THE PLÀT RÈIDH
F
B
T (BEN MORE)
RIVER OYKELL
Cb Cb Cc Cd t Cc Cd t Ce T A B^G B^G B^G A B^G

FIG. 63.—Highland structure. Showing an overturned fold in sedimentary beds enveloping a gneissic core. Section from the Oykell Valley across the Plat Reidh and Ben More, Assynt.

A. Lewisian Gneiss. B^G. Dykes in Gneiss. *B*. Torridon Sandstone. *Ca*. Basal Quartzite (Cambrian). *Cb*. Pipe-rock. *Cc*. Fucoid-beds. *Cd*. Serpulite-grit. *Ce*. Limestone. *F*. Intrusive Igneous Rocks. *T*. Ben More thrust. *t*. Minor thrusts.

5. While the planes of the major thrusts, along which the materials have been driven, usually dip at low angles to the E.S.E., yet they are frequently irregular both in direction and angle of inclination.

6. The outcrops of the major thrust-planes resemble boundary lines between unconformable formations because (1) there is always a complete discordance between the strata lying above and below the planes of disruption, and (2) each successive thrust may be overlapped in turn by a higher one.

7. Thrusts of smaller magnitude, when followed along the strike, may merge into folds.

8. By means of denudation, outliers of the materials lying above the planes of disruption have been formed, . . . the upper discordant members being separated from the lower by a fault with a circular outcrop.

9. The more powerful displacements were accompanied by differential movements of the materials, which resulted in the development of new structures.

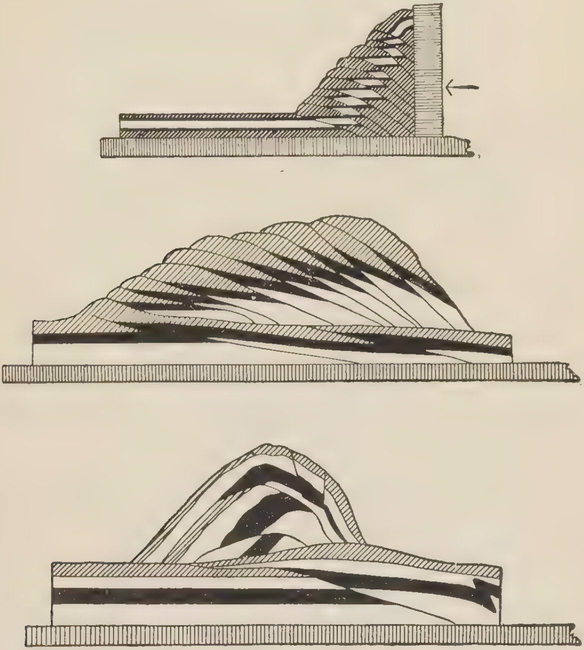

FIG. 64.—Illustrations of Highland structure. Experimental results illustrating the development of major and minor thrusts by pressure applied to beds of sand. (After Cadell.) The mechanical displacements occur along shearing planes, which develop from left to right, retrogressively, in consequence of piling up of the material in front.

The correct interpretation of the complex structure of the Scottish Highlands, after three-quarters of a century of study, was justly regarded as an achievement which reflected great credit on the two geologists, Peach and Horne, to whom it was chiefly

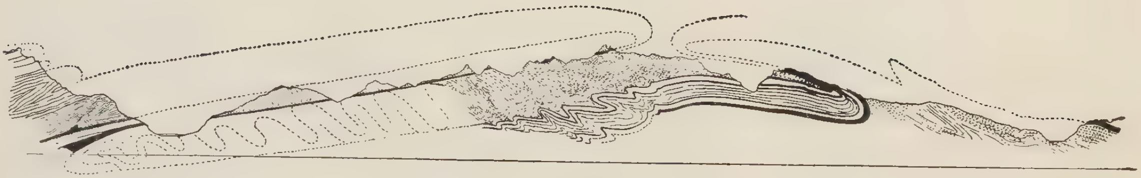

Fig. 65.—An over-thrust in the Alps. Section through the Glarner "double fold," as originally drawn by Heim; subsequently interpreted as an overthrust by Rothpletz; and since regarded as a part of the great "Decken," or "nappes" of which the Alps are supposed to consist.

Length of section about 15 miles. (After Heim, "Mech. der Gebirgsbildung." Profile XIII. Plate VII.)

due, and also as a discovery of a unique type of structure. It is unique, however, only because it was the first of its kind to be described. The mechanical conditions which gave rise to the great major thrusts and their associated minor thrusts and overfolds are probably not peculiar to this particular segment of the earth's crust, and similar effects of deformation may be expected to occur in other mountain ranges. The Highland type of structure is a specific example of a general effect.

Alpine Structure.—In the Alps and the Pyrenees overthrusts of very great displacement and extraordinary complexity are associated with overturned folds of unusual magnitude. Reference has already been made to the folds in connection with the account of folded zones (p. 45). We are here concerned with the overthrusts and their interpretation.

The earlier observers of Alpine structure contributed many details but lacked the basis of any comprehensive understanding. Heim [1] was the first to develop a general interpretation. All the emphasis of his training and observation placed folding before shearing, and he read the structures as overturns rather than as overthrusts, as is illustrated in Fig. 63. Rothpletz [2] recognized that overthrusts are dominant features of the structure, but interpreted them as having been displaced in more than one direction; that is, from southeast toward northwest, or from north to south, or from east to west, as the case might be. He thus came into contradiction with the contemporaneous school of Swiss and French geologists represented by Lugeon,[3] who assumes that all the movement was from southeast toward northwest. Lugeon followed Hans Schardt and Marcel Bertrand in recognizing that large mountain masses or mountain chains may be completely cut off from their foundations by faults, which are to be regarded as overthrusts. The significance of this fact can be inferred from an inspection of Figs. 66*a*, *b*, *c*, which represent the facts

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[1] Heim, A., "Mechanismus der Gebirgsbildung," 1878.

[2] Rothpletz, A., "Alpenforschungen," I–III, 1900–1908.

[3] Lugeon, Maurice, Les grandes nappes de recouvrements des alpes de Chablais et de la Suisse. *Bull.* de la société géologique de France, 1901.

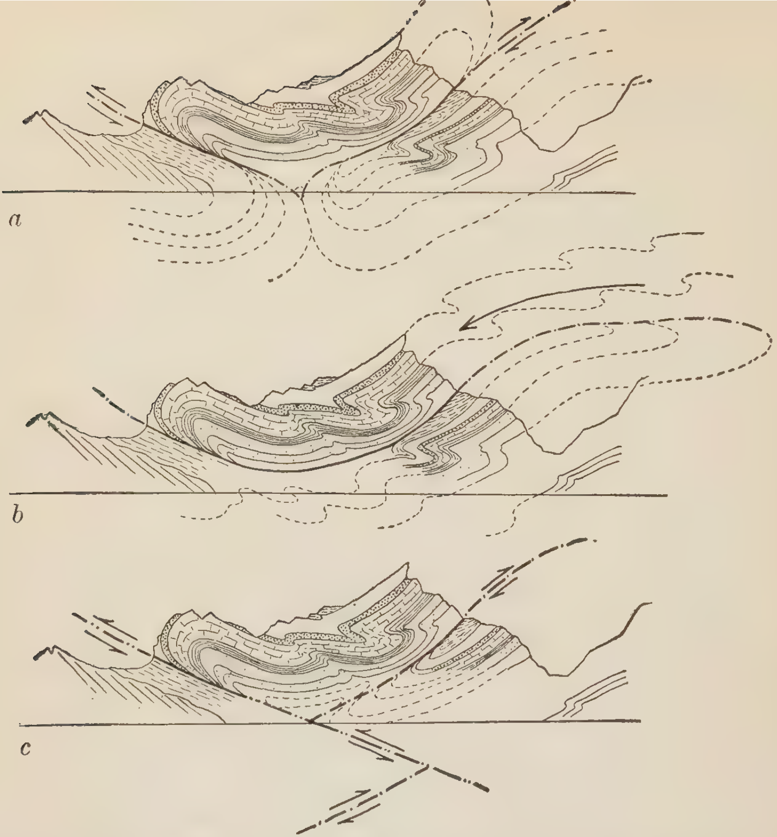

FIG. 66.—Interpretations of Alpine structure. Generalized section of the northern foothill region (Préalpes) *a* and *b* after Heim, Geologie der Schweiz, vol. II, p. 18.

a. Represents the idea of a fan-shaped anticline with compressed axial region and out-thrusts on both limbs; not now regarded as probable, but possible.

b. Illustrates the concept of an overthrust sheet or "Decke." The thrusts shown in Fig. *a* as two are here assumed to be one continuous thrust, which extended up to the right over the Alps. The mountain mass is regarded as representing the plunging "head" of the overthrust sheet, which is supposed to have been continuous to its "roots" south of the Alps and was thrust into its present position as indicated by the arrow.

c. Presents an alternative suggestion, according to which an older thrust from the northwest is supposed to have been sheared across and displaced by a younger thrust from the southeast, as observed by Bailey Willis in the Wildstrübel and vicinity of Lenk.

of an actual case and three interpretations of the deeper structure.

The first interpretation (Fig. 66*a*) assumes that the two thrust faults, which actually dip under the central mass, die out downward and pass into an anticlinal axis where the strata are squeezed out and may be pinched off. This is a fan-shaped or mushroom fold. It is mechanically possible and in some cases the idea may represent the facts.

The second interpretation (Fig. 66*b*) assumes that there is one continuous thrust plane which passes under the central mass and isolates it from the underlying strata. The attitude of the thrust plane is synclinal, and the section which now forms a trough is a remnant of some former extension of the thrust plane that is now eroded. Warped and eroded thrusts of this nature are well known from other regions and in themselves present no difficulties. The facts are reasonably regarded as indicating that the thrust developed at an early stage of compression and has since been warped up and down. It may even have been folded and displaced during later movements. The magnitude of the warping, folding, and faulting of the relatively old thrust plane should, however, be such that the hypothetical structures do not exceed mechanical possibilities. It is at this point that the theory originally proposed by Lugeon in 1903 and still widely accepted breaks down. Consult Figs. 67 and 68. (Plate XXIII, profiles 2 and 6, Heim.)

The idea developed by Lugeon involves the concept of overthrust sheets, called *nappes de recouvrement* or *charriage* in French and *Decken* in German. The German term is quite commonly used by English writers. An overthrust sheet is a thick layer of folded and faulted strata. It is bounded by thrust planes of great horizontal extent, both above and below. It may be identified by the age, stratigraphic sequence, and fossils of the strata composing it. Thus identified, the Alpine decken have been numbered and named; for instance, in Fig. 68.

No. V is the Monte Rosa Decke and No. VI the Dent Blanche Decke.

Now it will be observed by studying the sections that the

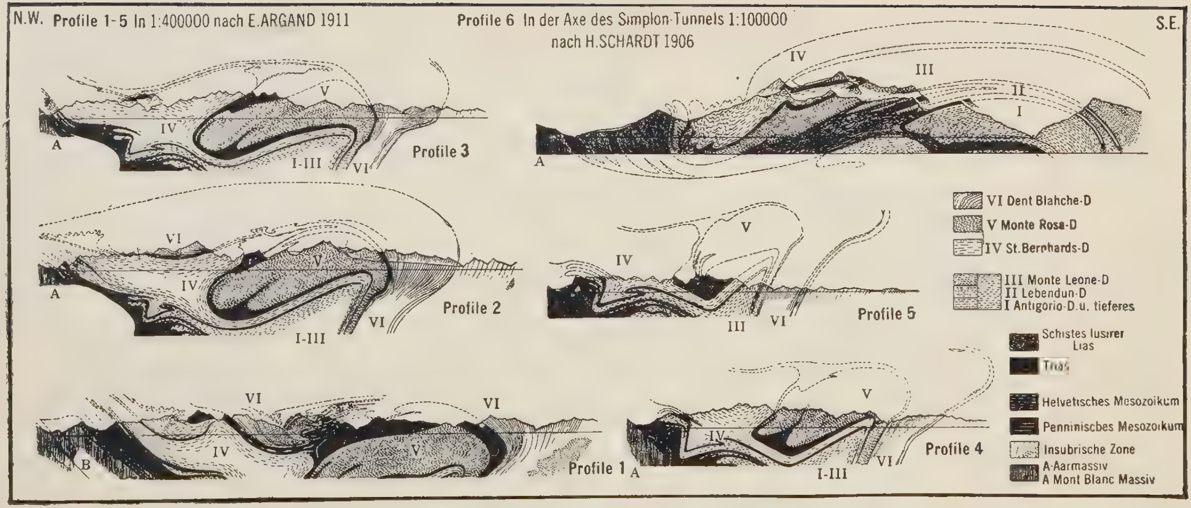

FIG. 67.—Sections through the Pennine Alps (Heim, Die Schweiz).

Monte Rosa Decke has been thrust over four older thrust sheets, Nos. I to IV, and that they are marvellously folded into each other. Again, the Dent Blanche Decke, No. VI, is represented as having been thrust clear over No. V from the southern to the northern side of the Alps, a distance of 30 miles (48 kilometers). Bearing in mind that Monte Rosa is 15,293 feet (4,638 meters) high, we may determine from the section that the height of the upper surface of the overthrust sheet is 44,000 feet (13,200 meters). The central portion of the sheet is called the *carapace*, the origin (which is at the right of these sections) is the *root*, and the northern end is called the *head*. It is maintained that each overthrust sheet has been forced out of the earth's crust at its root, that it has been pushed over all older decken, and that its head has plunged into the position in which it is now found. All that mass of the decken which is supposed to have been thrust over the Alps is assumed to have been eroded. Thus the separation of the heads from the roots is accounted for.

A concept so extraordinary, faced by mechanical and erosional difficulties of insuperable magnitude, could not without strong supporting evidence have gained the support of well-informed, earnest geologists, as it has. That evidence is stratigraphic and faunal. During various epochs in the history of the trough, where the strata of the Alps were deposited, the stratigraphic sequence on the northern side differed in lithology and fossils from the stratigraphic sequence and fossils deposited contemporaneously in the southern part of the trough. For instance, a thick deposit of mud in the north would be represented in the south by an alternation of limestone and shale or by massive limestone. In this connection the word *facies* is used. A facies is an assemblage of strata and fossils which represent a given geologic epoch. Any epoch may be represented in the Alps by a northern and a southern facies.

Now the argument runs to the effect that the *heads* of the decken which are now found overlying thrust faults in the *north* are of the same facies as the *roots* the same decken exhibit in the *south*. Therefore the strata of the heads must have been deposited originally in the south and could have reached their present posi-

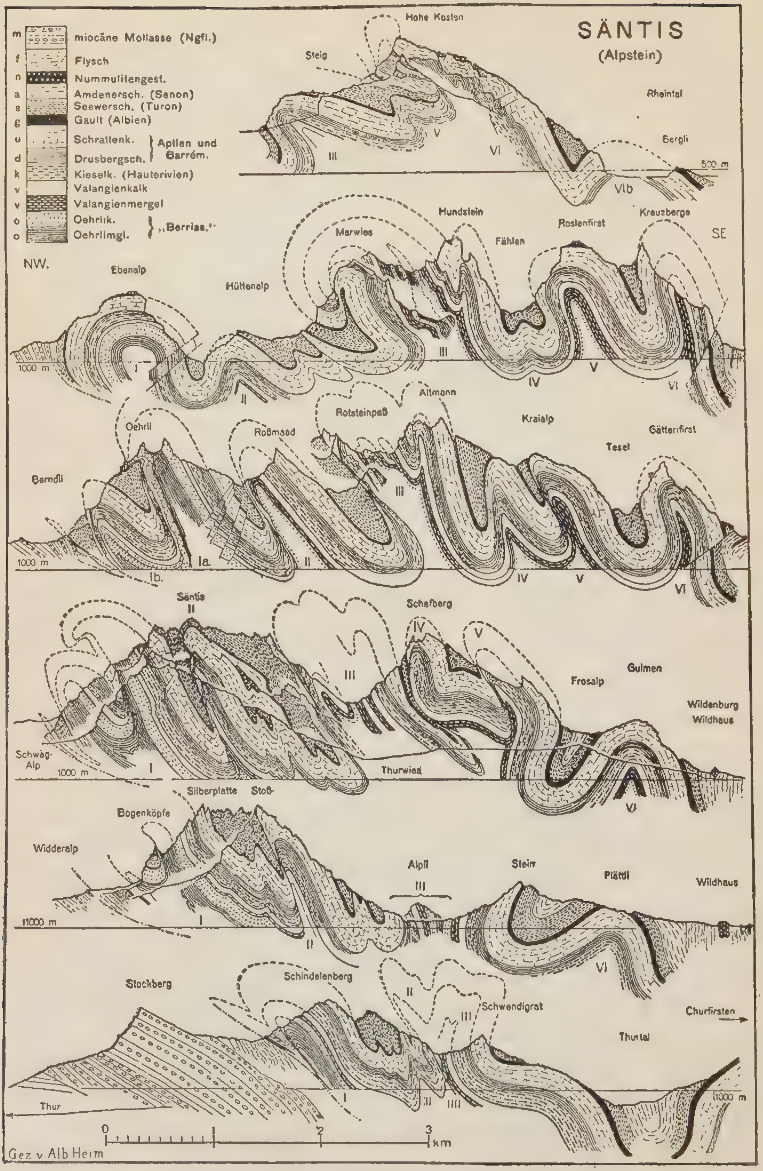

FIG. 68.—Sections through Mt. Säntis (Heim, Die Schweiz).

tions only by having been thrust over the mass of the Alps. Successive decken must have been thrust one over another in sequence.

This argument has been widely but not universally accepted. Those who remain incredulous have been answered by Albert Heim, who is himself the best informed of all Alpine geologists, as follows:[1]

> On reading their (the objectors') discussions one meets in nearly all cases the more or less clearly recognized origin of their opposition: they are unable to imagine the mechanics of the overthrusting. But neither have we succeeded in that as yet. The facts of the decken structure are so evident that there is no alternative but to accept them and to seek and wait for the understanding.

The strength of this position is the very intimate knowledge of stratigraphy, faunas, and structures of the Alps, gained during the last three quarters of a century by the indefatigable mountaineers who have devoted themselves to that geologic investigation. There is probably no part of the world, certainly none of equal extent and ruggedness, that has been so intimately examined, mapped, photographed, and dissected.[2] The weakness of the position is the assumptions, among which is conspicuous the idea of simplicity of stresses in the chaos of structures. Advocates of the decken theory maintain that all displacements have originated on the southern side of the Alps, and that all movements have been from south or southeast toward north or northwest. They justify this inference by the identity of the facies in the heads of the decken and the zone of the roots. These are, however, marine facies, such as accumulate under relatively broad, though usually shallow seas, and the identity of stratigraphy and fauna does not cogently demonstrate coincidence or immediate contiguity of the areas of deposition. On the other hand, the complexity of structures in itself requires the reactions of stress and counter stress.

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[1] Heim, Albert, "Die Schweiz," vol. II, 1; p. 30, 1921.

[2] The following recent works may be consulted to obtain an understanding of the views currently held by Swiss geologists regarding the tectonics of the Alps. The works are superbly illustrated with views, profiles, and maps. They have much the same relations to structural geology as it is usually taught in America that calculus has to algebra.

Heim, Arnold. (The son.) Monographie der Churfirsten-Mattstock-Gruppe, Text and Atlas. Beiträge zur Karte der Geologie der Schweiz, Neue Folge, Lief. 20, 1913.

Staub, Rudolph. Der Bau der Alpen, Versuch eine Synthese. Beiträge zur Karte der Geologie der Schweiz, Neue Folge, Lief. 52, 1924.

de Loys, Frederick. Monographie géologique de la Dent du Midi, Beiträge zur Karte der Geologie der Schweiz, Neue Folge, Lief. 58, 1928.

Collet, Léon, "Structure of the Alps," 1928.

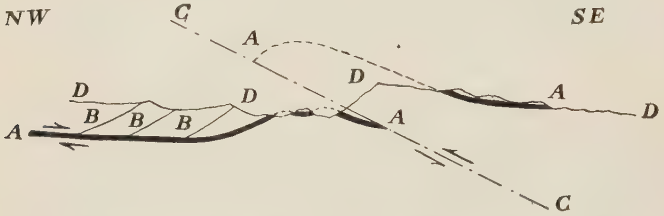

FIG. 69.—Diagram of intersecting thrusts observed near Lenk and in the Wildstrübel.

$AA'A''A'''$ = plane of a major thrust from the northwest. B, B, B = minor thrusts branching from the major thrust AA' and belonging to one system with it. CC' = thrust from the southeast, intersecting and disturbing the older thrust $AA'A''A'''$. DD' and $D''D'''$ = surface of erosion developed after the thrust $AA'A''A'''$ and before the thrust CC'; dislocated by the latter and involved in the elevation of the Hautes-Alpes.

Though it may be supposed that an active source of pressure existed in the Mediterranean region during all the ages of structural development of the Alps, it is mechanically unavoidable that the pressure from the south must have been met by resistance from the north. Moreover, it is probable that both would cause independent folds and thrusts, whether overfolds, overthrusts, underthrusts, or upthrusts depending upon the mechanical relations of the stresses in the strata and the relative rigidity of opposed members. The assumption that structures due to resisting pressure do not exist because all movements must have been from one direction prevents recognition of such structures if and where they do exist. Rothpletz was of the opinion that he recognized them.

The assumption of active pressure from the south and from the south only has been controverted on direct evidence in at least one case. In 1907 Bailey Willis examined a district in the Préalps (northern foothills of the central Alps) near Lenk, including the Wildstrübel, an outstanding peak of the Bernese chain and a typical example of the decken structure. The structure which he found is illustrated in Fig. 69. It consists of an older major thrust, $AA'A''A'''$, with minor thrusts, B, B, B, showing movement from northwest to southeast, and of a younger thrust, CC', from southeast to northwest. The interval of time between the dates of the two thrusts is demonstrated by the erosion surface $DD'D''D'''$, which is cut across the older system and is displaced by the younger. Lugeon answered Willis's interpetation, pointing out some errors of identification of strata, wherein the Swiss geologist is no doubt right, but neglecting to consider the physiographic and structural evidence which is the crux of the explanation.[1]

The structure of intersecting thrusts is indicated in Fig. 66*c* as an alternative explanation of the interpretations shown in *a* and *b*. However, the fact that there are intersecting overthrusts and that they do in one case replace a hypothetical decke may not justify a broad application of this interpretation of Alpine structures. It is a mistake to assume that the complexity of the latter can be explained according to any one formula. The strata are involved in folds, overfolds, recumbent folds, and thrusts,[2] in wide overthrusts and probably equally wide underthrusts, and in upthrusts, transverse shears, and other local displacements. The structures have themselves been folded and sheared in movements concurrent with or subsequent to their own development. Long intervals of erosion have intervened and removed parts of older structures before later ones were superposed upon them. The geologist who would unravel the tangled skein of successive events in the Alps must carry a dozen explanations in his head, not one alone, and possess great agility in changing his point of view.

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[1] Willis, Bailey, Report on an Investigation of the Geologic Structure of the Alps. Smithsonian *Misc. Collections;* vol. 56, No. 31, 1912.

Lugeon, Maurice, Beiträge zur geologischen Karte der Schweiz; neue Folge, Lieferung 30, 1914, seite 20 etc.

[2] Willis, Bailey, Thrusts and Recumbent Folds, a suggestion bearing on Alpine Structure. *Science,* n.s., Vol. XXV, pp. 1010–1011, 1907.

LOW-ANGLE UNDERTHRUSTS

The Conditions.—Referring again to Fig. 39, page 65 we may recall that the block *A* may be regarded as fixed in position and *B* may be forced under it. Such a displacement is an *underthrust.* The plane of the thrust may lie at any angle, but if the dip is less than 45 degrees the fault is a *low-angle* underthrust.

Underthrusts are much less generally recognized than overthrusts, and their existence is sometimes doubted because it is difficult to imagine space as existing or being made underneath a large wedge of the earth's crust into which another wedge could be pushed. There is of course no cavity in any case, but a wedge may be forced under, or a body of magma may be squeezed out, or rocks may change form and yield so as to afford space. Since large masses of the earth's crust can be displaced, it is a question only of the manner in which the forces are applied to them whether they slide over or are pushed under.

The mechanical conditions that give rise to underthrusting are discussed in the analytical section, pages 289–291. We here consider some of the probable occurrences.

Underthrust Folds.—In regions of simple folding it sometimes happens that the steeper limbs of two unsymmetrical anticlines face each other. Either one or both of them may have progressed to the degree of faulting and be traversed by a thrust fault. Several interpretations are then possible. If the syncline between the two anticlines be regarded as having been the stationary mass, both anticlines are overfolded or overthrust. If either anticline be considered as the stationary side, then it is underthrust and the other one is overthrust.

Examples of this type of structure occur in the Jura mountains and are illustrated in Figs. 31 and 32. They also occur in the southern part of the Appalachian folds, but are not so well developed there as in the Jura.[1]

In the cases cited the thrusts diverge downwards. In Fig. 66*a* two thrusts are shown which converge downwards, and if the structure be interpreted as a fan-shaped, faulted fold they may both be regarded as underthrusts or either one may be considered to be an overthrust and the other an underthrust. The designation depends upon assumptions concerning the direction of displacement and relative immobility of one or the other side of the structure.

Major Underthrusts.—There are examples of low-angle thrusts of great magnitude, which may be interpreted as overthrusts or underthrusts according to the assumptions that may be made regarding the direction of displacement. In North America, for instance, the thrusts that outcrop along the eastern border of the Rocky mountains and dip under the ranges (see page 106) are described as overthrusts on the assumption that the western part of the continent has moved eastward; but, if it were thought that the eastern part of the continent had been pushed westward, they would be underthrusts. No American geologist has yet suggested the latter interpretation, but a similar occurrence in Asia is either an underthrust or an overthrust according to alternative inferences.

This reference is to the great system of thrusts that outcrops along the base of the Himalaya range, where it impinges upon the Ganges trough. The main mass of the Himalayas consists of relatively old strata, whereas the southern foothills are formed of younger sediments. The latter were derived by erosion from the older rocks, but are over-ridden by them in consequence of the development of a series of thrusts. The thrust planes dip northward under the Himalayas. They are represented by Wadia,[1] after Middlemiss, as lying at a very steep angle; but, even though that may be the attitude near the surface, a lower dip under the mountains is indicated by the fact that the horizontal displacement is scores of miles, while the vertical is but thousands of feet.

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[1] SMITH, EUGENE A., Underthrust Folds and Faults. *American Journal of Science,* 3d ser., vol. 45, p. 305, 1892.

HAYES, C. W. and WILLIS, BAILEY, Conditions of Appalachian Faulting. *American Journal of Science,* 3d ser., vol. 46, pp. 257–268, 1893.

The fact of this great system of thrusts, which extends from the Punjab on the west to Assam on the east, a distance of 1,500 miles (2,400 kilometers), is well established; but there are differences of opinion as to the direction of the principal movements. Has Tibet been pushed southward over India, or has India been thrust under Tibet, or have both moved? The question has not been answered. The mechanical relations do not indicate a definite answer. The theoretical answer depends upon hypotheses which differ in their assumptions and divide different schools of geologic speculation.[2]

Sub-continental Underthrusts.—The Himalaya range faces the Ganges plain with a mountain front that is remarkably high and steep. The region of the plain was formerly a deep arm of the sea. There are other scarps similar to that of the Himalayas that now descend from the continental shelves into oceanic deeps. They are submerged and therefore beyond reach of observation, but there is reason to think that they also rise above great thrust faults, as the Himalayas do. For instance:

The Sierra Maestra, at the south end of Cuba, rises above sea to heights of 5,000 to 8,000 feet (1,300 to 2,400 meters), and the scarp descends below sea level into the Bartlett deep to depths of 21,000 feet (6,400 meters).

The non-volcanic plateaus of eastern Honshu, Japan, carry summit altitudes approximately 3,000 feet (1,000 meters) above sea, while the depth sounded in the adjacent Tuscarora deep reaches a maximum of 28,000 feet (8,500 meters).

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[1] Wadia, D. N., "Geology of India for Students," pp. 233–235, 1919.

Middlemiss, C. S., Geology of the Sub-Himalayas. *Memoirs* of the Geological Survey of India, vol. XXIV, part 2, 1890.

Anderson, Robert van Vleck, Tertiary Stratigraphy and Orogeny of the Northern Punjab. *Bull.* Geological Society of America, vol. 38, pp. 665–720, 1927.

[2] Willis, Bailey, Continental Genesis; *Bull.* Geol. Soc. Am., vol. 40, 1929.

The Aleutian islands, though largely volcanic, rise from a continental shelf that fronts a great deep of more than 23,000 feet (7,000 meters).

The Andes of Peru tower 18,000 feet (5,500 meters) above sea abreast of the Atacama deep that sinks to depths exceeding 20,000 feet (6,000 meters).

It is established by studies of these regions that they correspond with zones of intense horizontal compression, the visible strata being folded and overthrust in a high degree; and they are also known to be shaken frequently and violently by earthquakes. In these respects they resemble the Himalayas. So far as the evidence goes it points to the existence of great thrust faults, located at or near the bases of each high scarp and dipping in under the continental mass, as the " Main Boundary fault " of the Himalayas dips under that range. But in regard to these supposed faults, as in the case of the known fault of the Himalayas, there is room for difference of opinion regarding the classification of the thrust. If the continent is spreading and moving outward toward the ocean basin, as some infer, these are overthrusts. If, on the other hand, the bottoms of oceanic deeps are expanding and pushing under the continental margins, then the faults are underthrusts.[1]

[1] WILLIS, BAILEY, Research in China, Carnegie Institution of Washington, *Publication* 54, vol. II, pp. 123–125, 1907.

CHAPTER V

TECHNICAL DISCUSSION OF FAULTS

Classifications and their significance. Discussion of the geometry of faults, their geometric classification; types distinguished by the relation of strike of fault to strike and dip of strata. Criteria for determining direction of displacement; general; local; detailed features of fault surfaces. Evidence of joints, four cases: drag; plastic distortion, thinning, drag folds. Nomenclature of fault displacements; horizontal displacements; elongation and shortening; slip, heave, throw. Committee on nomenclature of faults. Committee's names. Tolman's names. Illustrative diagrams.

CLASSIFICATIONS AND THEIR SIGNIFICANCE

This chapter deals with the geometry of faults: their geometric classification, the direction of displacement, and the nomenclature used in the analysis of faults.

There are different classifications of faults for different purposes. We have already specified two: there is the old distinction between the class described as *normal* and the class designated as *reverse;* and because of the ambiguity attaching to these terms we have introduced the classes that we call *high-angle* and *low-angle,* to be used for descriptive, noncommittal statement. In Chapter IV we have also indicated that misinterpretation of the character of a fault may have serious results for a miner through the loss of his vein. Wrong interpretation is equally misleading for the geologist and has been the cause of prolonged controversies, some of which still persist. The discussion of the Rheingraben is a case in point. The economic and scientific difficulties resulting from imperfect understanding are unfortunately familiar to petroleum geologists.

It should not be necessary to emphasize the prime importance of considering the means by which to distinguish different kinds of faults, the direction of displacement, and the nature of the stresses concerned in the movement.

To avoid misapprehension we here re-define the familiar but ambiguous terms in the senses in which they are used throughout this book.

A normal fault is a fault that hades to the apparent downthrow. This definition does not carry any implication regarding the nature of the stresses that caused the movement. A normal fault may result from horizontal elongation of a segment and the downward attraction of gravity; or it may be an effect of vertical upthrust, which overcomes gravity and causes horizontal elongation. In both cases elongation is the effect.

A reverse fault is a fault that hades to the apparent upthrow.—This definition does not carry any implication regarding the nature of the stresses that caused the movement. A reverse fault may be caused by horizontal compression accompanied by vertical movement; or it may follow from horizontal compression and downward movement. The former is an overthrust, the latter an underthrust. The feature common to both cases is horizontal compression or shortening.

Normal or reverse faults or vertical faults of indeterminate character may result from horizontal displacement. If so, they are produced by compression.

In mining operations and in all other cases where the *direction of displacement* is the essential problem, it is necessary to determine whether the fault hades to the downthrow or to the upthrow. The displacement and hade being known, the continuation of any vein or other feature of the structure can be determined.

When, however, the problem has been solved to that extent, there will still remain the question that is of most interest, theoretically and sometimes practically: How did the forces act to produce this effect? If the fault hades to the downthrow there has been elongation in the direction of the dip, but it may have resulted from subsidence of one block past a relatively fixed block or from the upthrust of one block past the other. On the other hand, if the fault hades to the upthrow there has been horizontal shortening, but it may have resulted from overthrust of an upper block upon a lower or from underthrust of the lower beneath the upper.

The term normal fault applies to both of the cases involving elongation, and the term reverse fault applies to both of those that result in shortening; but neither normal nor reverse is a final designation from which we may infer uplift or subsidence, overthrust or underthrust. Herein lies a source of much confusion.

The solution of a fault problem therefore usually involves the determination of the direction of dip of the fault plane, the direction of the upthrow or downthrow, the direction of displacement, including both the horizontal and the vertical components, and also the absolute effect of the movements, whether up or down, over or under.

GEOMETRIC CLASSIFICATION OF FAULTS

A fault, although part of a curved surface and having some thickness, may be regarded as a plane over any small area, and so also may the surfaces of the strata which it cuts be treated as planes. Hence the geometry of faults and of the segments of strata displaced by them is the geometry of intersecting planes.

Planes intersect in lines which are called traces. A fault plane cuts a stratum or a vein in a straight line which is the trace of the fault with the stratum, or vice versa. Since the stratum is displaced by the fault plane, there are two intersections or traces of the fault with the stratum, and the distance between the traces is the apparent displacement of the fault.

We express the attitude of any plane, whether fault or stratum or vein, by its strike and dip, which are defined on page 24. And it follows that if we know the relation of the strike and dip of a fault in relation to the strike and dip of the strata, we can express the relation of the two planes to each other. In order to use these relations to establish a geometric classification of faults, the strike of the fault is taken as its principal character, and its position with reference to the strike and dip of the strata determines the class of the displacement.

In the course of fieldwork we first observe the geometric relations of the fault to the strata and thence determine the type of the fault. There are four principal types, which are distinguished as follows:

(1) Strike and dip of the fault are both parallel to the strike and dip of the strata—*a bedding fault.*
(2) Strike of the fault is parallel to, or nearly parallel to, the strike of the strata, but the dip of the fault cuts across the dip of the strata—*a strike fault.*
(3) Strike of the fault is perpendicular to, or nearly perpendicular to, the strike of the strata—*a dip fault.*
(4) Strike of the fault is oblique, forms a distinct acute angle with the strike of the strata—*an oblique fault.*

In a bedding fault the plane of movement is the bedding plane of the strata. The displacement may be in any direction whatever. It is not shown by the strata, which retain their continuity and parallelism, but may be detected by striations, by slickens, by offset joints or dykes, or by pinches and swellings.

Strike faults cause a repetition of strata, or a gap, in cross-section, according to the way in which the dip of the fault cuts across the dip of the strata and according to the normal or reverse character of the fault.

Dip faults cut off the strata across their strike and offset them to one side or the other. The obvious displacement is a horizontal one, but it may be occasioned by a vertical movement across inclined beds.

Oblique faults approximate the effects of strike faults or of dip faults, according as they strike more nearly parallel with the strike of the strata or perpendicular to it.

Any of these four types of faults—bedding, strike, dip, or oblique faults—may be either normal or reverse. Any of them may have a displacement parallel to the strike of the fault, or perpendicular to it, or oblique to it.

The direction of displacement, whether parallel, perpendicular, or oblique to the strike of the fault, is a further means of classifying faults according to their geometric relations. Thus:

(1) A fault on which one wall has slipped past the other in a direction parallel to, or nearly parallel to, the strike of the fault is a *strike-slip fault.*

(2) A fault on which one wall has slipped past the other down the dip of the fault, or has been pushed past the other up the dip of the fault, is a *dip-slip fault.*

(3) A fault on which the walls are displaced in a direction-oblique to the strike of the fault is an *oblique-slip fault.*

The dip-slip type is the oldest type of fault recognized and is the one most commonly described. The effect of a dip-slip is however, very often simulated by slips in other directions, and the tendency to assign all faults to this type is frequently misleading.

The movement on an oblique-slip fault is in a direction which makes an acute angle with the strike of the fault. The effect may actually be, or may appear to be, that of a normal fault or of a reverse fault.

It is important to avoid the confusion which may arise between the terms oblique fault and oblique-slip fault, recalling that an oblique fault is one whose strike forms an acute angle with the *strike of the strata*, whereas an oblique-slip fault is one whose displacement is at an acute angle with the *strike of the fault.* An oblique fault may be a strike-slip, dip-slip, or oblique-slip fault and an oblique-slip fault may be a strike fault, a dip fault, or an oblique fault. We have two kinds of classes. The first depends upon the relation of the strike of the fault to the strike of the strata, the second upon the direction of movement on the fault plane. The former is determined when we observe the strikes of the fault and strata, whereas the latter can be fixed only by ascertaining the true direction of the slip or push.

Strike faults which trend with the general structure of a region are called *longitudinal faults*, whereas dip faults which cross the general structure are called *transverse faults.* These terms find their application in descriptions of large areas and great structures.

CRITERIA FOR DETERMINING DIRECTION OF DISPLACEMENT

General Considerations.—An inference as to whether a fault is normal or reverse may be based upon the nature of the deformation throughout the district or province in which the displacement has occurred. Where folding and jointing are the dominant phenomena, reverse faults may be looked for and any seemingly normal fault should be challenged until positively identified as such.

To cite certain illustrations, we may mention the folded zone of the Appalachians, where normal faults are rarely associated with folds, or the strongly upthrust and overthrust ranges of the Rocky Mountains, where the nearly vertical upthrust faults have too often been classed as gravity faults simply because they had a small hade. Normal faults are also characteristic of the Colorado plateaus, so graphically described by Powell and Dutton, but the faulting is an incident in the general uplift. In a plateau region folding is an incidental effect and reverse faults, if any occur, are very exceptional and local. Regions of what may be called mixed structure are illustrated by the Coast Ranges of California, where the dominant effects of compression exhibited in upthrusts, overthrusts, and folding, are associated with normal faults, due to the tension of arched superficial beds or to the disturbance of equilibrium caused by uplift and tilting.

Local evidences of the direction of movement on a fault plane may be deduced from the displacement of related strata or dykes or other recognizable datum planes. The problem usually takes the form of identification of a fault encountered in mining or in geologic surveying with its extension in adjacent territory, where it may be more widely examined and the ends of a displaced stratum may be located on either side of it. Suitable surveys then suffice to determine the amount of the displacement between the exposures of this one datum plane and, given the line of movement, the displacement in any other direction on the fault plane can be determined mathematically. Practical problems of this nature are treated in the appropriate section, pages 364–367.

The required solution of the problem in these cases may be merely qualitative or quantitative. That is to say, it may be sufficient to determine the direction of movement, as between two possible directions, or it may be necessary to ascertain the amount of displacement in a particular direction and place. In case the movement on the fault plane was one of simple translation, all parts moving parallel to one another, the measurement involves no difficulty. If, however, there has been rotation of one block upon another, the solution becomes more difficult and demands that the displacements of at least two established points be known. Rotation is more commonly a factor in fault movements than has usually been recognized and should be looked for rather than neglected. Where there has been rotation, it is important that the data upon which a solution is based should be concentrated in as small an area as possible, to reduce the possibilities of error.

Direct evidences.—Details of fault surfaces observed on the fault plane itself or in the immediately adjacent rock may indicate the direction of movement. They consist of the effects of mechanical work done on the rock faces as they mutually pressed, crushed, and molded one another in dragging past. They may be described under the terms: *polish*, *scratches*, *striæ*, *furrows*, and *grooves; chatter marks; crushing* or *mashing; plucking; shearing* and its effects, *jointing*, *crescentic gouges*, and *gash veins; drag* and *drag folds.*

Scratches, striæ, furrows, and grooves are engraved or plowed lines, produced by a fragment or corner of hard rock penetrating the opposite surface as it is dragged along. The four words are used in their usual English senses: a scratch, a mere scratch, lacking significance; striæ, a number of lines, arranged in parallelism or in intersecting systems; furrow, a plowed depression of linear dimensions, but wider than a mere line and hollowed out by the removal of material; groove, a broad depression, produced by the removal of material or by pressing it aside, generally rounded on the bottom and often without definite margins.

A scratch is made by a point projecting from the opposite face. It starts where the point comes into contact and it changes its character as the point is worn down or as it is lifted off. If worn down the point broadens and the scratch widens in the direction of motion. Several scratches may thus join to form one broad one.

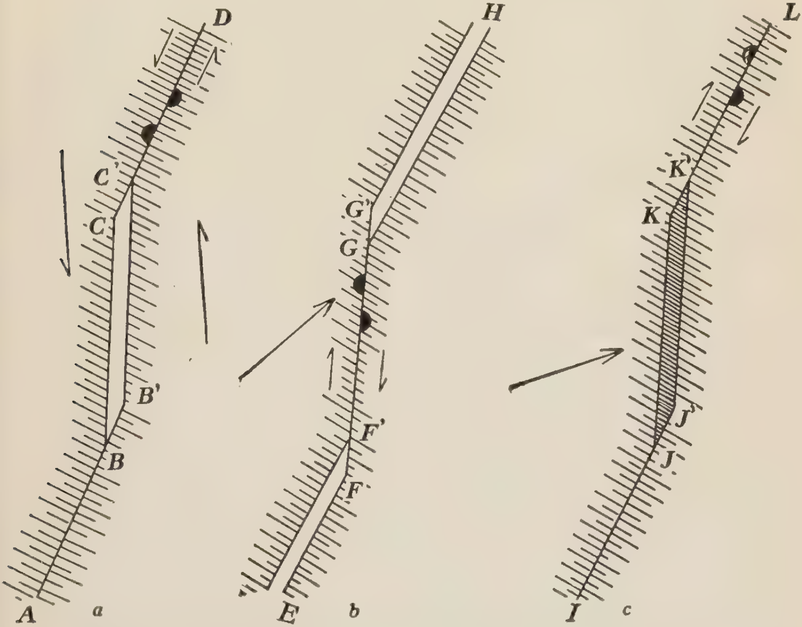

Fig. 70.—Diagram showing the effects of movements on zig-zag faults, producing openings and crushed sections.

If lifted off the point may cease to scratch gradually or suddenly, but to do so requires space between the faces, which can only be separated by the meeting of opposite shoulders. The shoulders should appear as higher surfaces on either one or both sides of the scratch and may very likely be highly polished. It is possible that the scratching tool may be rolled along and so leave a trail of scratches and pits. It does not appear that such marks would obey any rule. Or the tool may be crushed and begin to make several scratches, which would spread out in the direction of advance.

Striæ, in distinction to scratches, are more regular and more persistent. Nevertheless, we may describe them in the words of Chamberlin,[1] who in writing of glacial striæ says:

> Striæ differ widely in respect to the perfection and character of their definition. This apparently resulted partly from the form of the cutting tool, partly from the looseness or firmness with which it was held, partly from the smoothness or roughness of the surface in which it was inscribed, partly from the texture and lamination of the rock, both of the tool and the bed, and partly from the rate and irregularity of the motion.

Striæ may be interpreted as scratches with reference to the direction of movement, blunt ends, and diverging lines advancing. It is to be noted, however, that if the surface is wavy at right angles to the striations, the pressure of the tool may have varied in a manner to modify the character of the lines.

Furrow is a word which implies that the material has been turned out to one side, forming a ridge beside the valley. We cannot expect the ridge to survive on a fault plane, and the valley which remains is simply a broad scratch. It seems possible, although the writer has never observed it, that the margins of a furrow may show distinctive effects of plowing or dragging. Plowing implies the action of a tool which projects forward and would rip up slivers which would point backward and be broken off at their thicker, forward, end. A dragging tool, on the other hand, would tear out loose irregular pieces, whose form would be governed solely by the structure of the furrowed rock.

Grooves may be wide furrows with a rounded cross-section, where material has been ground off, or they may be molded grooves such as a finger makes when drawn over a mass of putty. The furrow groove does not differ from other furrows except that it may exhibit chatter marks or crescent-shaped fractures, which are described further on. The molded groove is characteristic of the molding of the surface of the more yielding rock mass to fit the irregularities of the opposing face, which may be of the same or of harder material. The effect is quite different from that of scratching, since the modeling may be accomplished by yielding to a considerable depth in the mass without breaking the surface.

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[1] Chamberlin, T. C., Rock Scorings of the Great Ice Invasions. U. S. Geol. Surv., *Seventh Annual Rept.*, p. 216, 1888.

The molded groove is an effect of plastic deformation and may vary from a fine line to a flat, spreading hollow, It may be straight or curve around the outlines of a raise. The sides may overhang. Large grooves often comprise many smaller ones. All the surfaces are rounded and in cross-section pass into one another smoothly.

Molded grooves tend to be parallel among themselves, but they do fan out and in such cases the divergence is commonly, if not universally, in the direction of the forward movement of the opposed face.

Hard particles, such as pyrite crystals in slate, or masses, such as concretions, chert nodules, or niggerheads, tend to remain in relief on the modeled surface. They then present a push side to the movement, resisting it, and have a lee side, which is protected from it. Two types of ridges result, the *spur* and the *trail.*

The spur points from the hard particle backward toward the advancing, opposite face. It consists of the softer rock material which is packed against the obstruction. It lies in the re-entrant angle which is formed by the over-riding face as it rises over the resistance. In this position the spur is exposed to the full pressure of the advancing face and is therefore usually highly polished. Its form is that of an acute cone, which lies with the apex directed backward. Molded grooves divide at its apex and pass around the obstruction, diverging forward.

The trail is a ridge which survives in the lee of a hard particle or mass, by which it has been protected from the over-riding face. Its base lies against the protecting block and it extends forward, gradually diminishing in height and possibly in width as it gets out from under the lee. It may be polished, but is often less smoothed or even left rough, because it is not so severely squeezed. The molded grooves which pass on either side of the obstruction tend to continue parallel to one another beyond it and thus give to the trail a cylindrical form.

Chamberlin describes trails as most characteristic of glaciated surfaces, and mentions an example of a spur as an exceptional development.[1] The spur would seem to be of more common occurrence on fault surfaces, and for this reason: beneath a glacier the projecting boulders dig away the rock surface, much as a chisel digs into wood, and they clear away the material up to the obstruction, as the chisel cuts up to a knot. The spur has no chance to form. But where one face of a fault is pressed into another with a force that molds them mutually into one another, there is no digging. An obstruction lifts one surface off of the other, forces them apart, and leaves a space in which material may remain or into which it may be squeezed by the excessive pressure on either side of it. Thus the spur is formed.

Chatter marks are fractures which occur in deep furrowed grooves or gouges and, being a mechanical effect due to the gouging, are limited in occurrence to that association. They cross the groove at right angles, but are curved and present the convex side toward the rear in the direction from which the gouging point moved. Chamberlin describes them as very characteristic of large glacial grooves.[2]

Crushing is a common effect of excessive pressure on the surfaces of hard rocks, like quartz, and takes the place with them of the modeling produced in softer rocks. A crushed area may well be called a *bruise*. The rock is more or less minutely granulated and the surface depressed. If it be assumed that the bruise was caused by a prominence of the opposite face, which in turn was also crushed as it advanced, then the area of excessive pressure should widen in the direction of movement. Thus a bruise, if it have an elongated and triangular form, indicates the direction of displacement.

Mashing is a term which was introduced by Van Hise to cover the effects of excessive granulation by crushing, accompanied by the displacement of the granules and often by recrystallization involving flow of the rock. When crushing passes into this extreme stage the surfaces are molded to each other and the effects can no longer be distinguished by the eye alone from molded grooves or hollows.

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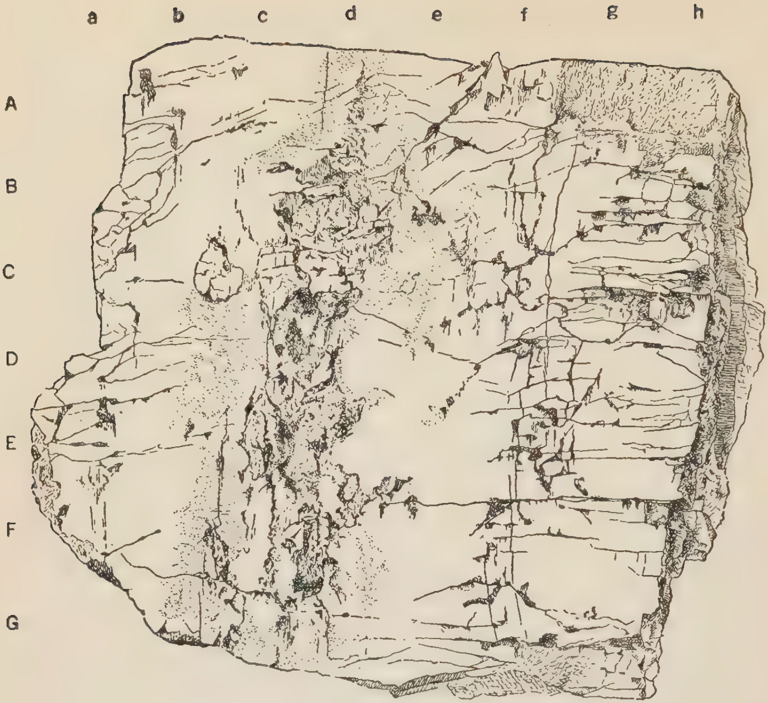
[1] Chamberlin, T. C., Rock Scorings of the great Ice Invasions. U. S. Geol Surv., *Seventh Annual Rept.*, p. 245, 1888.

[2] Op. cit., p. 247.

Plucking is an action by which particles or pieces of the face are torn out and carried away. The term is borrowed from glacial geology, where it is used in the same sense, but for larger masses. It is a common action of glaciers because the ice not only grasps, but embraces exposed blocks and takes them with it. Plucking from a fault face is the action of excessive local pressure and implies that in front of that great pressure there was a condition of less resistance or a space, in consequence of which the loosened piece could leave its bed and be carried on. Plucking, therefore, takes place on the lee side of an obstruction to the movement, and the piece plucked out may include a part of the obstructing body. Thus a spur may lead up to a blunt, broken end, from which the hard particle that caused the formation of the spur has been plucked off. Or where a miniature fold has been raised across the line of movement, the layers on the farther, advanced, side are often torn away.

Plucking from crushed surfaces may also occur where there is no apparent obstruction to the advance of the opposite face. In these cases a dislodged piece of rock has been pressed down in the rear and raised in front by an advancing prominence of the opposite face. Often the piece is merely rotated in its bed and remains inclined backward at a slight angle to the polished face. This kind of plucking may be observed in various stages of development on bruised quartz surfaces.

A piece plucked out is usually broken off and therefore leaves a rough bed. In this respect plucking differs from shearing. The rear side of the hole left by plucking is in the lee and retains its roughness, especially if it be steep. The advance side of the hole, on the other hand, is exposed to abrasion and is often smoothed or polished. This is a common means of determining



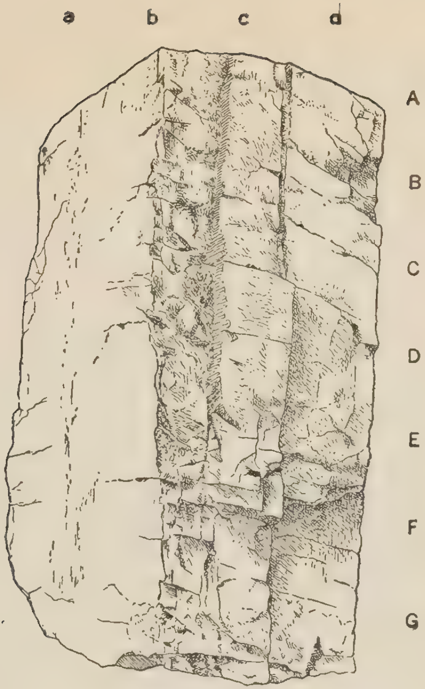
(*a*)

Fig. 71.—Specimen of vein quartz, showing a polished surface, and illustrating the criteria for determining the direction of movement on a fault. These criteria are as follows:

Considering first the large drawing representing the polished surface, when the fingers are drawn over this surface, in the direction from *A* to *G*, the surface feels perfectly smooth. If they are drawn over it in the opposite direction, the fingers encounter sharp projecting shoulders. This indicates that this surface has moved from *G* toward *A*, relative to the other side of the fault.

At *A–d* may be noted an irregularity or bruise which starts in a point, and broadens until at *B–d* and *C–d* it is considerably wider. This has been made by some projection on the other surface of the fault plane. To apply the rule, the projection moved from the narrow point toward the wider part of the bruise, deepening and widening it as it progressed. In other words, the block pictured moved toward the point of the bruise, or from *G* toward *A*, thus confirming the statement made above.

At *C–d*, or a little below it, is a hollow, with a steep side toward *A*, and a gentle slope toward *G*. At *C–g* is seen another similar hollow. These are due to plucking, the material removed having been carried away from the steeper side, again showing that the pictured block moved upward relative to the other side of the fault.



(*b*)

Turning now to the end view of the specimen, we see running from *C–c* to *D* a curved fracture, which makes an acute angle with the under surface, pointing downward. There are several other fractures parallel to this one. We can now think of the specimen as a block in a fault, with the masses on either side moving in opposite directions. If our conclusions regarding the direction of movement on the large face (*a* to *b* in the end view) are correct, the mass to the left of the specimen moved downward, hence the mass to the right must have moved upward. The fractures make a fairly high angle with the surface, and are not straight, nor are they clean cuts. This would indicate that they are tension cracks, developed by the drag on the fault surfaces. In such cracks, the acute angle points toward the direction in which the fractured block moves. This indicates that the under surface moved down relative to the mass to the right of the specimen, and the left-hand surface, that pictured in the larger drawing, moved up, from *G* toward *A*, again confirming the original conclusion.

These tension cracks developed by friction must not be confused with shear planes, which develop due to compression and movement. Such planes are generally more regular, straighter, and make a smaller angle with the surface. The danger of confusion lies in the fact that shear planes point in the opposite direction, relative to the direction of movement, from that assumed by the tension fractures. That is, if they were developed in this case, they would point downward to the left, instead of to the right.

the direction of advance of the opposite face. Even when the roughness cannot be distinguished by eye, the finger will feel the difference between the upstanding rear faces and the worn down front margins of the small cavities in the polished surfaces of hard rocks. In a bruised face, in which the bits of rock may have been but slightly pushed forward and raised in front, it is also possible to recognize the difference. The finger should be held at right angles to the direction of movement and passed gently back and forth.[1] Care should be taken not to confuse a plucked hollow with a crescentic gouge, as the two present the steep facet of the depression in opposite directions. The plucked hollow is, however, much the more common.

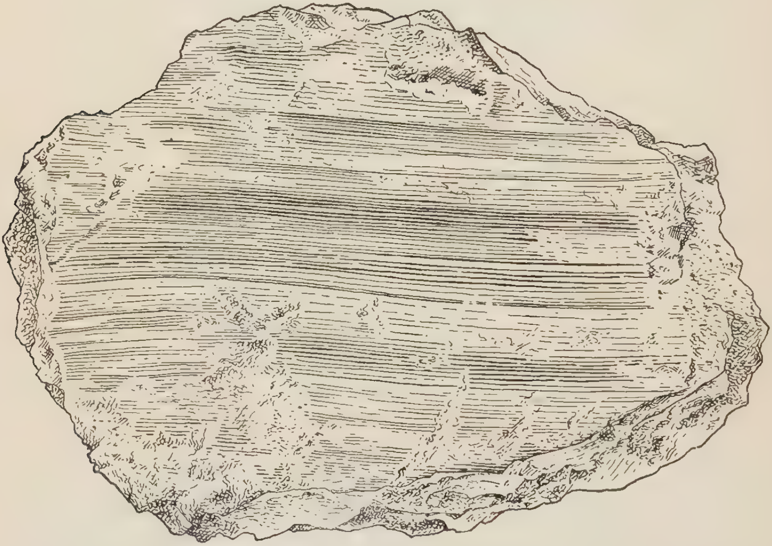


FIG. 72.—Specimen of quartz vein showing slickenside with molded and polished grooves. The plucked surfaces indicate that the movement of the overlying mass was from left to right. Four-fifths original size.

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[1] I am indebted to my colleague, Professor C. F. Tolman, Jr., for calling my attention to the delicacy of this test in the case of polished quartz surfaces.

The crescentic gouge is an effect of *conoid fracture*, according to Gilbert,[1] or of shear, which has a distinct form and interpretation. It is produced by pressure against a surface which is inclined backward, toward the opposing face, and which yields by a fracture similar to that which would be produced by a blow (conoid fracture) or by shear. The distinction is difficult and for the present purpose unimportant, since the form would be the same. The fracture or shear inclines forward into the rock at a gentle angle and is concave upward in cross-section. A sliver or flake is thus loosened from the face and may be broken off at the butt end, leaving a vertical fracture. The latter, which is ordinarily curved, faces the direction of motion and presents its concavity toward it. It is thus oriented in a position which is the opposite of that of a plucked hollow and of chatter marks. Crescentic gouges may be looked for on the push side of a rise where the surface is inclined toward the opposing face, which moves against it.

Evidence of Joints.—The evidence presented by joints depends on the relative ages of the fault and joints. Four cases may be distinguished, namely:

(*a*) When the joints are older than the fault displacement.
(*b*) When the joints are contemporaneous with the development of the plane of parting on which faulting occurred.
(*c*) When the joints are contemporaneous with the fault movement.
(*d*) When the joints are younger than the faulting.

In the first case the evidence of the direction of movement is that of displacement of the joints, as would be the case with a bed, vein, or other reference plane which had been offset by the fault. In faults of any magnitude this is not a reliable criterion, as it is impossible to identify individual joints on opposite sides of the fault. In faults of small displacement, however, it may be an important criterion, as the direction of displacement on small faults may serve as a clue to that on larger ones, and the tiny joints and fissures offset a fraction of an inch along the small ones may be significant.

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[1] Gilbert, G. K., Crescentic Gouges on Glaciated Surfaces, *Bull.* G.S.A., vol. 17, pp. 303–314, 1906.

Note.—"Gouge" is here used in the sense of a groove and not as miners use it to designate clayey selvage.

Either of two principal types of joints may be developed contemporaneously with faulting, that is, compression joints or tension joints. The former are apt to develop simultaneously with the development of the plane of parting of the fault, the latter are more apt to be effects of the drag on the fault plane. In regions where mineralization has occurred the two may be distinguished by the absence of vein filling in the former and its presence in the latter.

The mechanical relation of compression joints to the displacement on the faults is that of the relation of two sets of shearing planes originating in the same set of forces. If the joints developed with the plane of parting of the fault, then the two may be analyzed to show the direction of the original pressure, as described in Chapter IX, on the mechanics of shear. If the joints developed due to movement on the fault plane, as is possible or even probable in the case of large faults, they are a result of the rotational stress set up by the friction of the fault plane. They will make an acute angle with the fault plane, which will point in the direction in which the block on the opposite side of the fault has moved relative to the block in which the joints occur. This is illustrated by Fig. 73. It is obvious that joints so oriented will tend to be closed by the movement, hence they will not be apt to be materialized. They will be clean shear planes, and will be more or less evenly spaced.

Tension joints, on the other hand, will form an acute angle with the fault plane pointing against the direction of movement of the other block, hence they will tend to be dragged open, and are often characterized by vein filling. Such small veins constitute one form of gash veins, and the term *gash* implies the tension which formed the initial opening.

Drag.—The effect produced when two surfaces of rock are pressed closely together and moved past one another, provided one or both of them be plastic or flexible, is called *drag*. Massive, rigid rocks do not show the effects of drag, since when stressed beyond the elastic limit they yield by shearing instead of by plastic distortion or bending.

Plastic distortion is characteristically developed on the surfaces of clay rocks. They become smeared over the fault plane, sometimes taking a very high polish, sometimes forming a layer of gouge, which obscures or even prevents the development of significant markings.

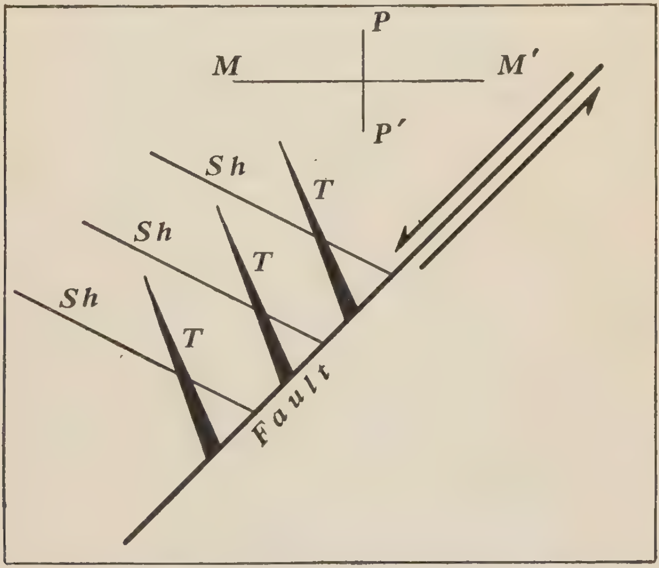

Fig. 73.—Shear joints, *Sh*, and tension joints, *T*, developed in the hanging wall of a fault by the movement on it. The fault is shown as normal, the effective force being gravity. The position of the axis of elongation is shown by *MM′*, that of shortening by *PP′*.

The thinning out of the overturned limb of an anticline, which may go to the extreme of thrust faulting, is a form of drag that is often a phase of plastic distortion accompanied by minute shearing, as was first pointed out by Heim [1] (Figs. 18 and 19).

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[1] "Mechanismus der Gebirgsbildung."

In the development of schists, by the rotation of mineral particles into parallel positions and by the growth of new minerals with parallel orientation, we may recognize the extreme effects of drag in materials which are plastic in the sense that they may be distorted without fracture. These phenomena may be limited to a fault plane, or occur throughout a fault zone, or pervade large masses of schist, but in all cases there have been displacements, either local or distributed, which constitute faults, and the effect is one of drag. Unfortunately these plastic effects are usually not significant criteria of the direction of movement.

Drag becomes significant when it involves bending or folding. Where a fault traverses strata, the ends are commonly bent back with reference to the direction of movement of the block in which they are, or forward in the direction in which the opposite face has moved. Since this is true of both sides of the fault, but in opposite directions, the ends bend toward one another and may become tangent to one another, parallel to the fault plane (Figs. 18 and 19). The extreme development of this form of drag is characteristic of thrust faulting, where the pressures are very great, but the ends of strata may also be bent in displacements occurring on normal faults, the weight of the downthrown mass being sufficient to cause the flexure.

In faulted sedimentary or other bedded rocks the deflection of strata in consequence of drag is one of the most valuable criteria by which to ascertain the direction of displacement. It is illustrated in Figs. 18, 56, 57, 58, and 63.

Where a fault plane lies nearly or quite parallel with the bedding of a faulted mass, as it often does in stratified, slaty, or schistose rocks, the dragging of one stratum over another may produce local folds, known as *drag folds.*

A drag fold on a fault plane usually consists of an anticline and a syncline, comprising three limbs. The fold is unsymmetrical or overturned, with the steeper or overturned limb facing in the direction of movement of the over-riding mass. In thin bedded shales and slates or laminated schists, drag folds are often very small or microscopic. They frequently pass into overthrusts, which take the orientation of shearing planes, lying at an acute angle, less than 45 degrees to the fault plane, with the apex directed forward with the overthrust mass.

Drag folds are also common in shales which are involved in large anticlines and become distorted as heavier beds adjust themselves to the folding. As the strata move past one another, as great thicknesses bend, the outer ones crowding up out of the synclines toward the anticlines and the inner ones pushing from under the anticlines down under the synclines, any thick bed of shale becomes a zone of displacement. It is dragged in opposite directions on its upper and lower surfaces and is forced into a system of drag folds, which are much more complex than the major structure of which they form a part. In these cases the drag folds are usually overturned and often overthrust, and always in the direction of the crest of the great anticline. This is an important means of determining the position in a fold of a body of strata, which may be so isolated or unidentified that its true stratigraphic position is in doubt. Drag folds on a large scale were first described by Heim [1] (Fig. 65).

Nomenclature of Fault Displacements.—Faults and fault displacements have many names, and unfortunately the names are used in various senses by different groups of technical men. There are the miners and the mining engineers, whose terms are few and comprehensive; fault, slip, throw, and heave are employed to designate a variety of structures or displacements and consequently have no exact meanings. There are geologists in general, who follow the usage of textbooks, which are many of them not up with current discussion. And there are specialists in fault structures, who have developed a modern, technical use of terms that has the advantage of being exact, but is understood by but few. The writer who would not be misunderstood must, therefore, take pains to make his meaning obvious.

The most obvious fact about a fault, when it is encountered in mining, is the direction of its inclination or hade. Inspection of Figs. 74 and 75 will serve to show that the hade is different in a normal fault from what it is in a reverse fault, and this fact is used to formulate a rule by which they may be distinguished, as follows:

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[1] Op. cit.

A normal fault hades to the apparent downthrow, whereas a reverse fault hades to the apparent upthrow.

The use of this rule in mining is evident. Let us suppose that the fault has been approached from the left and the point V'' has

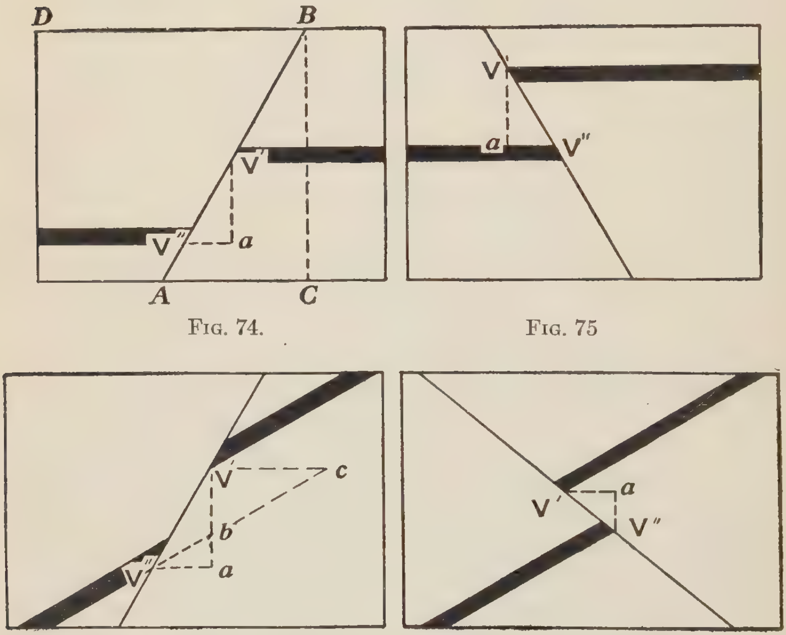

Fig. 74. Fig. 75

Fig. 76. Fig. 77.

Figs. 74 to 77.—Diagrams of normal and reverse faults.

been reached. The miner is confronted by a blank wall, the fault plane. He observes its shade, which in Fig. 74 is toward him, and he knows, perhaps, that the fault is a normal fault. Then, according to the rule, he has approached the fault through the downthrown block and the continuation of the coal bed lies above. Or, let us assume that he has driven his tunnel from the right (Fig. 75), and having arrived at V' finds the fault hading away from him. It is clear that he is in the upthrown block and the continuation of the bed lies below him, at V''.

The correctness of his assumption, on which he proceeds to drive a slope through the solid rock, depends on whether the fault is really a normal fault or is in fact a reverse fault. If it be the latter, each of the inferences in the preceding paragraph is reversed, given the identical conditions, and the bed will not be found in the direction in which it is mistakenly sought. Hence the importance of knowing positively the nature of the fault, whether normal or reverse.

In the assumed case (Figs. 74 and 75), the fact that the strata are horizontal gives the problem the simplest possible aspect. The difficulties are not materially greater in the examples presented in Figs. 76 and 77, where the strata dip at a considerable angle, because in these simple sections it is implied that the displacement has been directly *down* or directly *up* the dip of the fault plane.

A somewhat different case is presented in Fig. 78, in which a bed or vein is shown as being displaced on the fault FF in such a manner that the segment on the right may be described as lying either *below* or *to the right* of the segment on the left. Take, for instance, a point V. It may have moved in the direction VV' or VH, or VV'', or in any intermediate direction. Let VH be horizontal. Then we may say: If the displacement has been in any direction below VH, the hade of the fault plane is toward the downthrow and the fault is by definition a normal fault. But if the displacement is in any direction above VH, the hade of the fault plane is under the upthrow and the fault is a reverse fault.

If a miner were seeking the continuation of a vein, which continued indefinitely up and down, he would find it by driving his crosscut in the right direction from V. If, however, he sought the other part of a local bonanza, a misinterpretation might carry him above or below it and, striking the vein in a relatively barren section by driving along VH, he would not know whether to go up or down to find the ore.

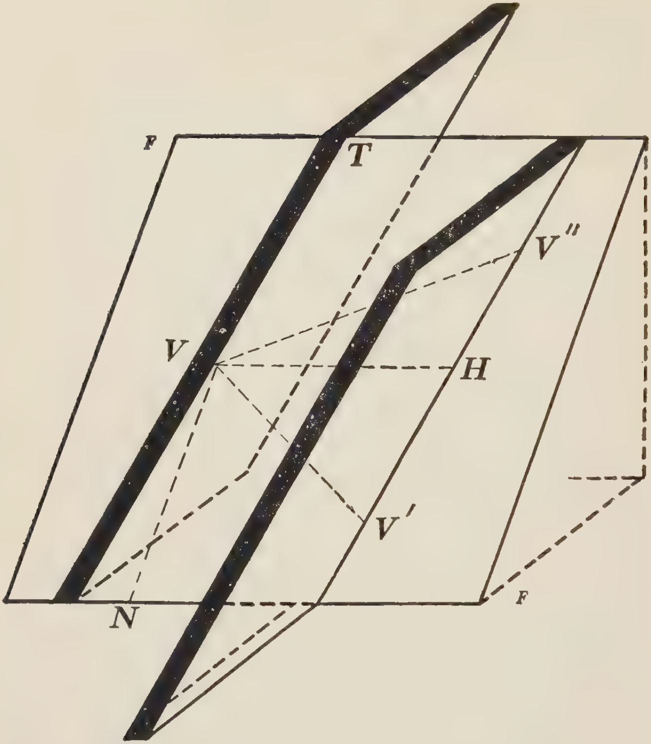

FIG. 78.—Diagram of a vein displaced by a fault which is apparently a normal fault, but which may be either normal or reverse according to the direction of movement.

VN is in a vertical plane and represents the displacement directly down the dip of a normal fault. Any displacement between *VN* and *VH* corresponds to a normal fault.

If the direction of movement were from *V* in any direction between *VT* and *VH* the fault would be an upthrust.

If the displacement were from *V* to *H*, the fault would be a horizontal fault, neither normal nor reverse.

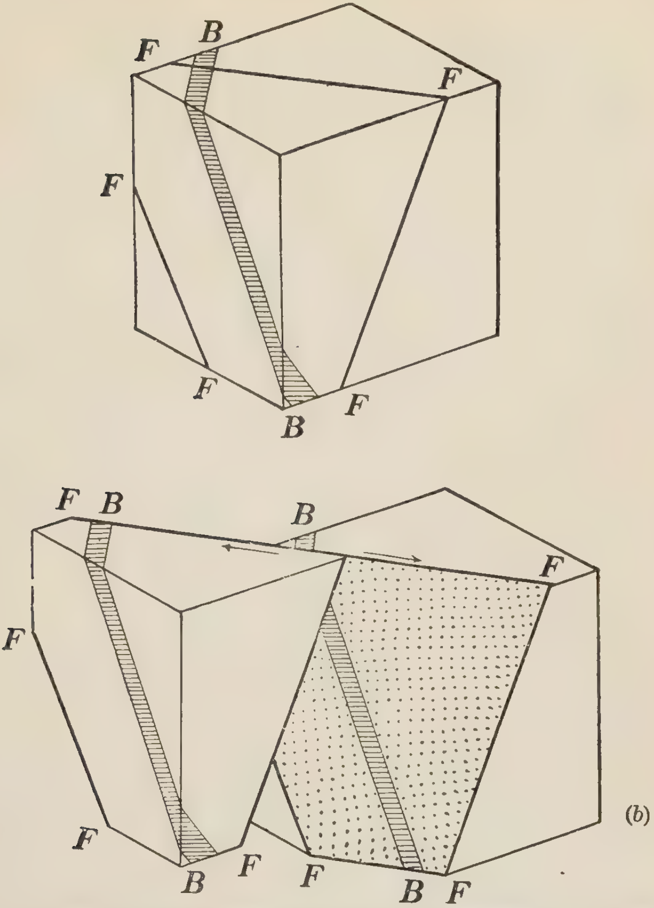

Fig. 79.—Block diagrams showing the effect of horizontal displacement in simulating normal faulting. (After Ransome. *Economic Geol.*, Vol. I, 1906.)

(*a*) View of a cube of rock traversed by a dike and a joint plane, but not faulted.

(*b*) View of the same cube with the parts displaced horizontally. The dike, *BB*, appears to be thrown down and the fault plane hades under the downthrow, as in a normal fault, yet there has been no downward movement.

It will be observed, furthermore, that the force which has caused the fault is presumably different, according as the movement has been below or above the line VH, that is to say whether it has had a downward or an upward directed component combined with a greater or less horizontal component. A downward component is due to gravity, which would tend to pull the displaced mass directly down, it is true, but which may be deflected by unequal resistances in the direction of the least resistance. An upward component, on the other hand, must be attributed to compression, which may be directed upward or diagonally as the resultant of various components of the force and the resistances. From the point of view of the theory of faulting, involving the nature and origin of the active force, it is important that the proper interpretation of the movements should be reached.

We may next turn our attention to the effect of faults in lengthening or shortening a segment of the rocks. By reference to Fig. 74 it will be seen that there is a gap between V' and V'', which separates them horizontally. The length of the faulted segment has been correspondingly lengthened by the normal fault. On the other hand, in Fig. 75 we may observe that there is an overlap of the faulted bed, as is shown by the relative positions of V' and V'', and the segment has been shortened by reverse faulting.

Putting these observations in the form of a general statement we may say: *Any segment of rocks which is parted by a true normal fault is lengthened* (*extended*) *horizontally, whereas any segment which is traversed by a reverse fault is shortened* (*compressed*) *horizontally.*

The word *true* in the preceding rule is to be contrasted with *apparent.* Defining a normal fault as one which hades to the downthrow, we must distinguish those which really do have that inclination from those which only seem to have it. For it has been shown in the immediately preceding paragraphs and in Fig. 78 that an inclined stratum or vein may apparently hade to the downthrow, when in fact it has a horizontal or a reverse displacement and is not a normal fault at all. The above rule must be applied with care.

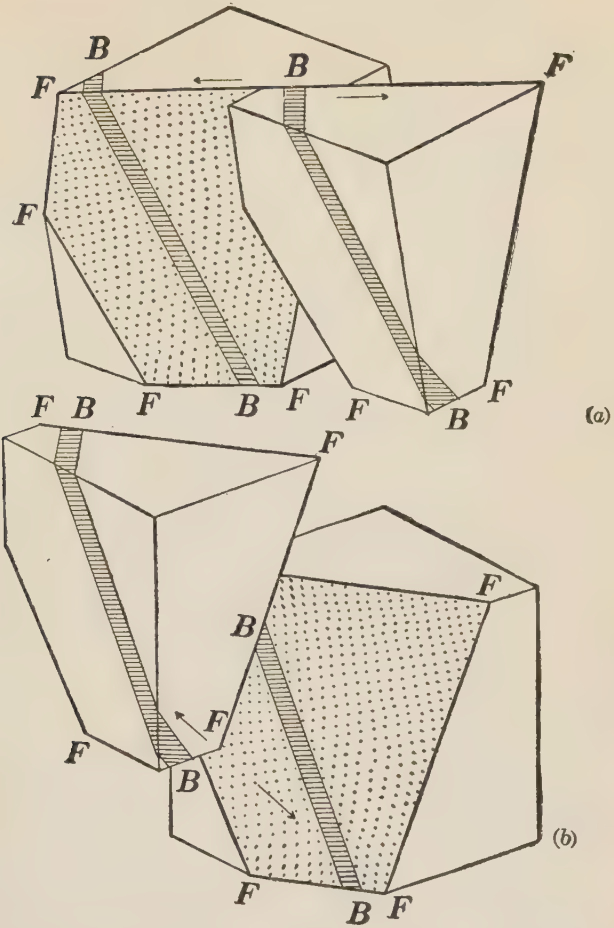

Fig. 80.—Block diagrams showing the effect of horizontal displacement in simulating reverse faulting. (After Ransome. *Economic Geol.*, vol. I, 1906.)

(*a*) View of the cube shown in (*a*) and (*b*), with a horizontal displacement which simulates a reverse fault. The dike *BB* appears to be pushed up and the fault plane hades under the upthrow, as in a reverse fault, yet there has been no upward movement.

(*b*) View of the same cube displaced diagonally by a movement between the horizontal and a direct upthrust, yet seeming to have suffered normal faulting.

Very early in mining it became necessary to distinguish the amount of vertical displacement occasioned by a fault from the horizontal displacement. Consider a right angle triangle and let the hypothenuse represent a fault plane along which horizontal strata have been displaced. Let the triangle stand with one side horizontal, the other vertical. Then, if the length of the hypothenuse represents the *slip* on the fault plane, the horizontal side will be the horizontal component of that displacement, called the *heave* of the fault, whereas the vertical side will be the vertical component of the displacement, called the *throw* of the fault.

Throw and heave thus correspond respectively to the vertical and horizontal sides of a right angle triangle, of which the dip-slip is the hypothenuse. These three simple terms suffice in general to describe the dimensions of a fault. The slip (first published in 1913 with this meaning) is the displacement on the fault plane, which geologists too often erroneously call the throw. It indicates the real magnitude of the movement, whether it is given in feet, thousands of feet, or miles. The ratio of the throw to the heave indicates the attitude of the fault plane, since when the throw is twice or more than twice the heave we have a decidedly high-angle fault (hade, 27 degrees or less), whereas if the throw is only half the heave or less we have a distinctly low-angle fault or thrust (dip, 27 degrees or less).

Exact statements, however, require that the position of the vertical plane formed by these three hypothetical lines should be defined with reference to the strike of the fault, and to avoid inconveniences of statement and interpretation the rule is laid down that *throw and heave shall be taken in a plane at right angles to the strike of the fault.*

The corresponding slip will also lie in this plane, the plane of the dip of the fault, and to distinguish it from slips in directions oblique to the vertical or even horizontal, it is called the *dip-slip.*

Throw, heave, and dip-slip are the elements of a fault in the dip-plane only. and they are, therefore, adequate to describe the movement only in case the displacement has been directly up or down the dip-plane. If there has also been horizontal movement, a fourth element is required to represent the horizontal component of the true displacement. This element, when measured horizontally in the fault plane, corresponds in direction with the strike of the fault and is therefore called the *strike-slip*.

To illustrate: the earthquake on the San Andreas fault in 1906 occasioned a vertical displacement of about one foot and a horizontal displacement of 20 feet. The hade of the fault is nearly vertical. Stated in fault terms this would read: The throw was about one foot and nearly the same as the dip-slip. The heave was very small. The principal movement was in the direction of the strike-slip and amounted to as much as 20 feet.

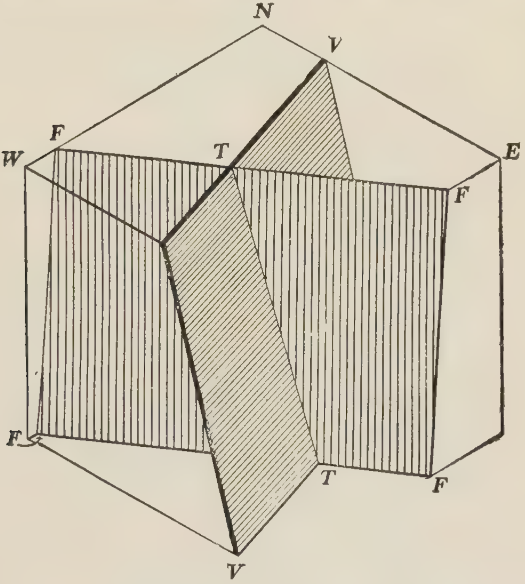

FIG. 81*a*.—View of the intersection of two planes without displacement, as seen in isometric perspective.

FF a plane.
VV a plane.
TT trace of *FF* with *VV*.
WNE corners of the isometric cube. The front of the cube is removed.

It is a common practice of geologists to draw sections at right angles to the strike of strata and without reference to the strike of any faults which may traverse them. The strike of the strata and that of the faults often differ, and the dimensions of the throw, heave, and dip-slip of the faults differ correspondingly in a section at right angles to the strata from those which they would have in a section at right angles to the strike of the fault. Therefore, when it is desirable to draw sections in any other position than normal to the strike of the fault, the dimensions obtained for the elements of the fault should be stated as the apparent throw,

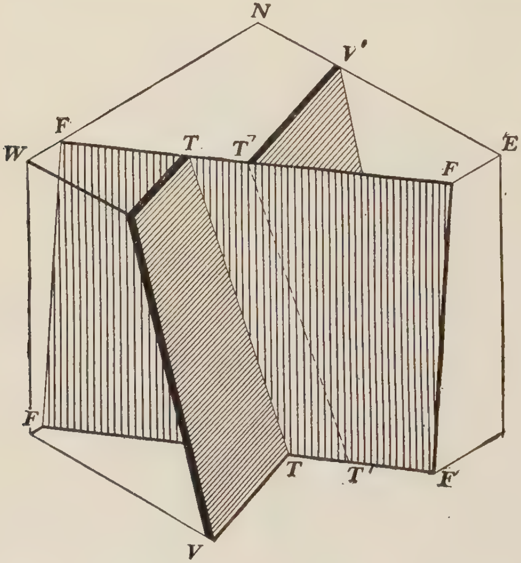

Fig. 81*b*.—View of the intersection of two planes with displacement, as seen in isometric perspective.

FF fault plane.

TV and *T'V'* segments of the plane *VV'*, which has been displaced.

TT and *T'T'* traces of the fault plane *FF* with the segments of the faulted plane.

WNE corners of the isometric cube, the front of which is removed.

heave, and dip-slip, to distinguish them from the true values of those components of the movement.

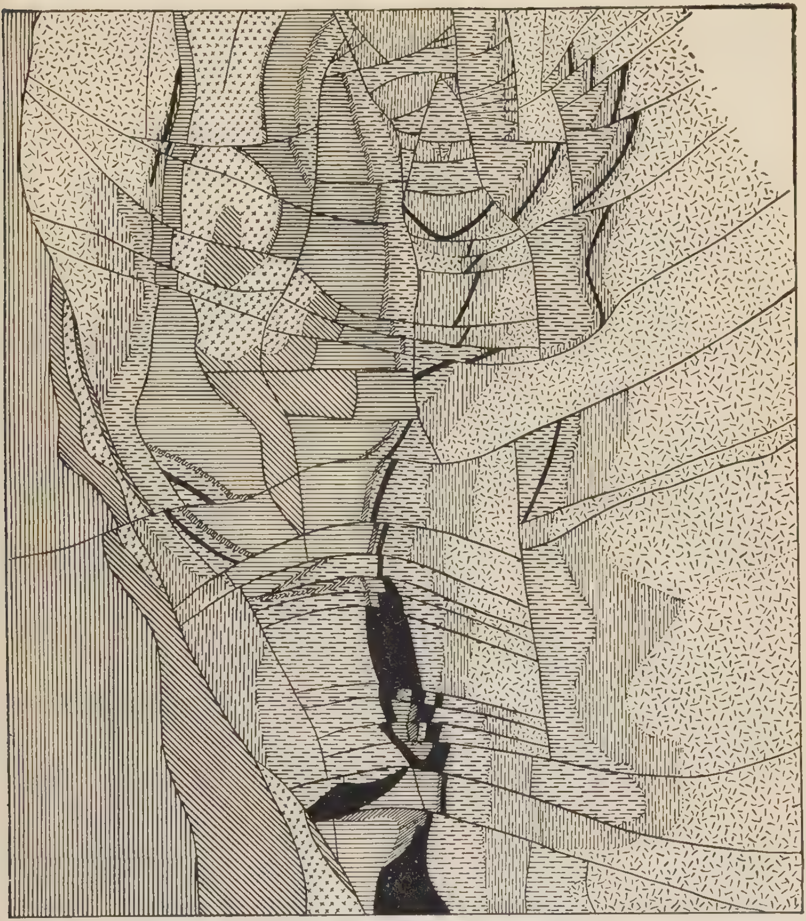

FIG. 82.—Illustration of faulting in the Aspen district, Colorado. Geologic map of Tourtelotte Park. (After Spurr. U. S. Geol. Surv., *Monograph* XXXI, Scale: 1 inch = 3,000 feet.)

In general geologic studies, in which we deal with large masses of strata whose visible section is restricted to surface outcrops, all the rest being either eroded or buried, it is rarely possible to measure the displacements of faulted mountain blocks with accuracy, and mathematical niceties of definition are too often overlooked. Geology suffers accordingly, for loose language is the expression of loose thinking and leaves the reader in doubt as to the value of the observations which it records.

In mining, on the contrary, precise surveys above and below ground govern all well-conducted operations, and precision in observation demands exactness in statement. The proper use of fault terms should, therefore, be the rule. It is not so, however, partly because language is often used carelessly, partly because the development of the terminology of faulting is comparatively recent and has not yet become widely known. The exact definition and precise usage of the terms employed in describing faults

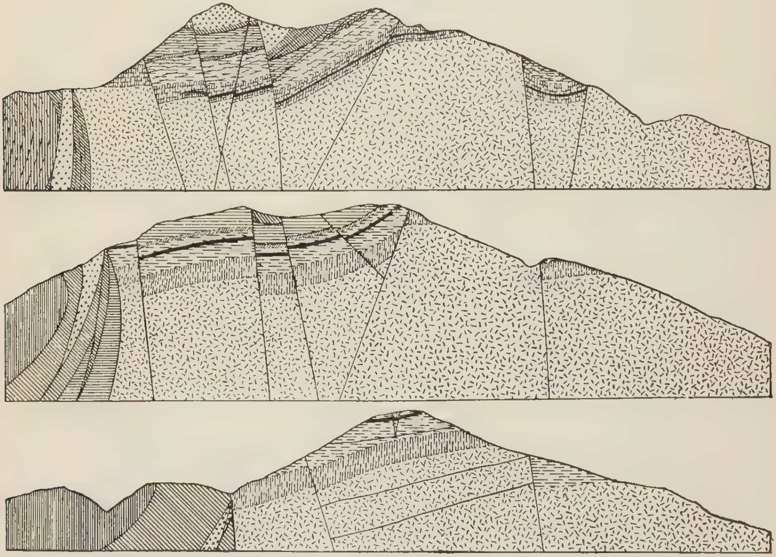

FIG. 83.—Illustrations of faulting in the Aspen district, Colorado. Sections of Tourtelotte Park, looking north. (After Spurr. Scale: 1 inch = 3,000 feet.)

is, none the less, imperative in the interest of the proper understanding of fault mechanics.

Spurr [1] first called attention to the fact that displacements accompanying faulting might take place in any direction. He wrote:

> In this movement one part of the fractured rock mass may move upon the other in any direction—up, down, sidewise, or obliquely—according to the conditions, which are different in each instance.

He recognized that oblique movements require more precise terms to define their components than those which had sufficed under the assumption of direct up and down movements, and he proposed a set of six names to designate different parts of a fault movement, namely:

> For general outline work, where accurate data are not obtainable, the terms *throw* and *vertical separation*, referring to the measurements of a fault at its intersection with a vertical plane, and the term *heave* or *offset*, indicating the measurement of a fault at its intersection with a horizontal plane, are adopted. . . . Where more complete data are obtainable, the terms *total displacement*, *lateral separation*, and *perpendicular separation* are adopted.

Spurr's proposed terms did not come into general use, largely because very few writers discussed faults with sufficient exactness to employ precise names for the details of movements and also because his terms did not agree in meaning with previous usage, especially the two old terms, throw and heave. Their meaning is given in relation to that of other systems on page 171.

Ransome [2] pointed out that:

> The terms normal and reverse as commonly applied to faults have very little real significance. They express merely a location of the faulted beds, dikes, or other structures to the plane of the fault. They do not, unless we make unwarranted assumptions, indicate the kind or direction

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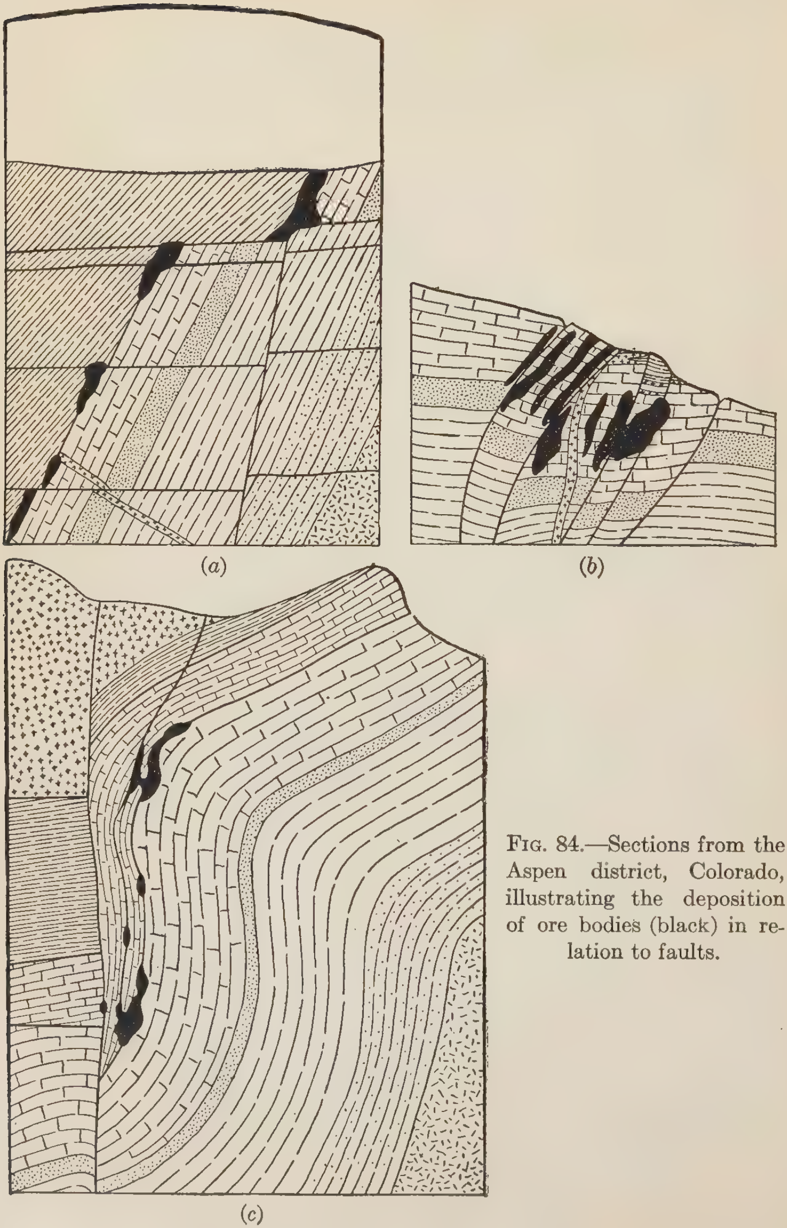
[1] Spurr, J. E., Geology of the Aspen Mining District, Col. U. S. Geol. Surv., *Monograph* XXXI, Appendix, pp. 253 to 256, 1898.

[2] Ransome, F. L., The Directions of Movement and the Nomenclature of Faults, *Econ. Geol.*, vol. I, pp. 777 to 787, 1906.



(a)

(b)

(c)

Fig. 84.—Sections from the Aspen district, Colorado, illustrating the deposition of ore bodies (black) in relation to faults.

of movement or whether tension or compression was the dominant stress at the time of dislocation.

The stress of Ransome's paper is upon the occurrence of horizontal movements on fault planes, and he rightly emphasizes the fact that such movements are far too common to be overlooked, as had been done by even the best writers. The gist of his argument is expressed in the excellent diagrams taken from his paper, Figs. 79*a* and *b*, and 80*a* and *b*.

Tolman [1] in 1911 proposed a very elaborate and logical system of fault nomenclature, developed as a result of his experience with fault problems in mining practice and in teaching. He groups the possible measurements under the names of "displacements, throws, heaves, and separations," and distinguishes under each name five different measurements, which bear certain definite relations to the fault plane, to vertical and horizontal planes, and to the plane of the faulted vein or stratum. His terms are defined in the following paragraphs, along with those proposed by the committee appointed by the Geological Society of America.

Following a discussion of fault movements, which was published in Economic Geology,[2] the Geological Society of America named a committee to draw up and propose a nomenclature of faults, which submitted its final report at the meeting of December, 1912.[3] The conclusions of this committee, whose work extended over three years and comprised the consideration of all published material pertaining to the subject, as well as correspondence with a wide circle of geologists, are worthy of being followed, as representing the nearest approach to an agreement in discussions involving technical precision in descriptions of the complex movements of faulting. The terminology recommended by the committee is accordingly given precedence in the following statement of the modern terminology of fault displacements.

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[1] Tolman, C. F., Jr., How Should Faults Be Named and Classified? *Econ. Geol.*, vol. II, pp. 506-511, 1907.

[2] *Econ. Geol.*, vol. 2, pp. 58, 182, 295, 433, 506, 585, 601, 803; 1907.

[3] Reid, H. F., Davis, W. M., Lawson, A. C. and Ransome, F. L., Report of the Committee on the Nomenclature of Faults, *Bull.* Geol. Soc. Am., vol. 24, pp. 163–186, 1913.

It is assumed that the reader is familiar with the methods of projection used in the simpler problems of descriptive geometry. It is only by their use that we can represent the position of any line in space. They enable us to present it in its true dimension, or according to some scale that we can determine, in a plane which we assume to suit our convenience. They thus make it possible for us to see and to measure the lines that represent movements of masses in the earth, which are actually buried beyond observation or which have been eroded. Any builder uses these methods when he draws the plan or elevation of a house on a sheet of paper. He assumes that the paper is parallel to the floor or to the wall of the building and he projects the lines representing the length, width, or height upon the paper according to the scale which he has adopted. We use similar projections in the study of earth structures, including faults.

The thing which we measure in faults is the displacement of one mountain mass with reference to another with which it was formerly connected; or the distance by which one part of a dissevered stratum or vein is separated from the other part; or the exact length of a line which we draw to connect a known point on one side of the fault with the point which was in contact with the first before the displacement occurred.

There are five planes on any one of which the components of displacement may be measured. They are:

(1) The fault plane itself.
(2) The dip plane of the fault.
(3) The dip plane of the strata or of the vein.
(4) The plane perpendicular to the trace of the fault with the strata or vein.
(5) The horizontal plane.

According to the beautifully systematic nomenclature proposed by Tolman, all measurements made in the fault plane should be called *displacements*, all those in the dip-plane of the fault should be *throws*, all those in the plane perpendicular to the trace should be *separations*, and all in the horizontal plane should be *heaves*.

The committee of the Geological Society of America endeavored to assemble a group of terms which would " make no changes in words which have a recogized meaning " and would " follow the best usage where a word is used in different senses." The result is therefore necessarily unsystematic. According to the conclusions of the committee certain terms have the following applications:

Displacement is a general term by which to designate the relative movement of the two sides of a fault, measured in any direction.

Slip designates any measurement in the fault plane. The slip in a specific direction may be distinguished by an appropriate adjective and we thus get *dip-slip*, denoting the slip in the direction of the dip of the fault, and *strike-slip*, referring to the component of the displacement parallel to the strike.

Shift is introduced to describe the displacement of masses on either side of a complicated fault zone. Its use implies that the shifting of the masses has been occasioned by movements on two or more related faults, distributed in a zone of greater or less width. The terms *dip-shift* and *strike-shift* designate the components of movement in the direction of the resultant dip or strike respectively. Shifts are measured parallel to the zone of faulting, to its dip or strike, etc., the general position of the zone taking the place of the attitude of the fault surface of a clean-cut fault.

Separation is proposed as a word of rather general significance, to be applied to measurements between the two surfaces of the faulted bed or vein, taken in any direction. Thus, in mining, a tunnel, driven through a fault from the vein on one side to the same vein on the other and measured from footwall to footwall or from hanging to hanging, would give the horizontal separation in that particular direction. A shaft, similarly located and measured, would represent the vertical separation.

Throw is restricted by the committee to the vertical distance between the two ends or edges of a faulted bed or vein, taken in a plane at right angles to the strike of the fault.

Heave is similarly restricted to the horizontal distance between the two ends or edges of a faulted bed or vein, taken in a plane at right angles to the strike.

The preceding definition of throw and heave is made more exact by the insertion of the requirement that the elements shall be measured between the edges of the severed stratum or vein. Any other vertical or horizontal measurement is excluded. Thus, if we have a dip-fault which crosses an inclined stratum whose traces with the fault plane are shown in Fig. 85 as *ac* and *bd*, the throw is *bk* and not *cf*, while the heave is *ak* and not *ae*.

Geologists wishing to designate the horizontal distance between the two occurrences of a displaced stratum, or mining engineers describing the driving of a tunnel from one segment of a vein through a fault to the other part, may refer to *ae* as the heave of the fault; but that is not according to the definition. The line *ae*, if measured in a plane at right angles to the strike of the fault, represents the *horizontal separation*, according to the committee; or, if it is measured in the plane at right angles to the strike of the strata, it is the *offset* or *normal horizontal separation*.

It has been stated that the dimensions of faults may be measured in any one of five planes, enumerated on page 160. Of the five there are two which are employed either by one or the other of two groups of students, but usually not by both. The dip-plane of the strata is a plane of projection preferred by geologists, but less used by miners; and the plane perpendicular to the trace of the fault with the vein is a reference plane used only by a few mining engineers. In Tolman's[1] classification the former was not considered, whereas in that of the committee the latter was not recognized.

The details of the authoritative nomenclature of faults as formulated by the committee of the Geological Society of America [1] are given in the accompanying diagrams and the appended descriptions. Tolman's names are also stated. For the arguments which governed the committee, the original paper should be consulted.

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[1] TOLMAN, C. F., Jr., How Should Faults Be Named and Classified? *Econ. Geol.*, vol. II, pp. 506–511, 1907.

In order that they may have definite meanings the names of fault measurements are referred to certain lines and directions and are taken in certain planes, all of which are shown in Fig. 86, which represents a fault plane, a fault, the faulted vein, and three other planes.

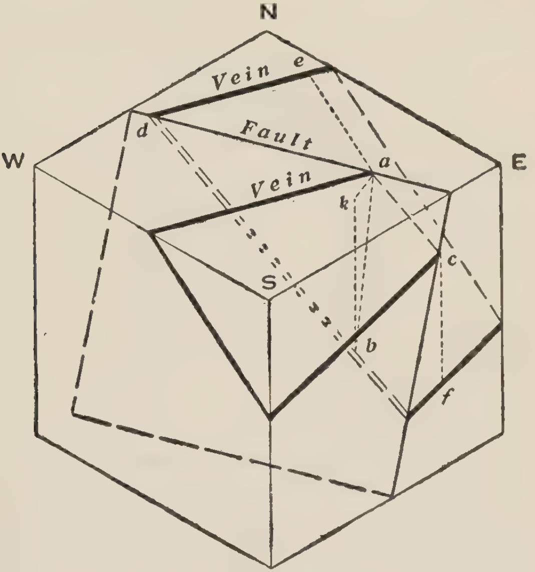

FIG. 85.—View of a dip-fault.

ac and *db*.	Trace of faulted vein on fault.
bk.	Throw.
ak.	Heave.

The fault plane is *FFFF*. The faulted vein is *VVTT* in front of the fault plane and $V'T'T'V$ behind it. The traces of the vein with the fault plane are TT and $T'T'$, and we may see that TT appears to have slipped down from its former position in contact with $T'T'$. Thus the fault has the appearance of a normal displacement, but it may be noted that the same effect would be produced by a horizontal shift of the front block from the right, where TT might have been in contact with $T'T'$, toward the left to its present position. The character of the fault is, therefore, indeterminate.

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[1] REID, H. F. and others. Report of the Committee on the Nomenclature of Faults; *Bull.* G. S. A., vol. 24; pp. 163–186, 1913.

Three planes, *Df-Df*, *Dv-Dv*, and *Pt-Pt*, are shown cutting across the fault plane and the faulted vein. An infinite number of planes might be laid across the system, but these three are selected because each one has a definite mathematical relation to either the fault plane or the vein or the trace of the vein with the fault plane.

Df-Df is a vertical plane which makes a right angle with the strike of the fault. The trace, *FF*, which the fault plane makes with the horizontal upper surface of the cube, is the strike of the fault, and the angle which it makes with *Df-Df* is 90 degrees. *Df-Df* is the dip plane of the fault.

Dv-Dv is a vertical plane which makes a right angle with the strike of the vein. The trace, VV, which the vein makes with the horizontal upper surface of the cube, is the strike of the vein, and the angle which it makes with *Dv-Dv* is 90 degrees. *Dv-Dv* is the dip plane of the vein.

Pt-Pt is a plane which is laid perpendicular to the trace, TT, of the vein with the fault plane. It is therefore inclined to the horizontal in all cases except when TT is horizontal. *Pt-Pt* is perpendicular to both the fault plane and the vein, the angles made by its traces with the fault plane and the vein being right angles. *Pt-Pt* does not, however, cut the strike of either the fault or the vein at 90 degrees.

Measurements of the displacement of a fault may be made in any plane whatever, chosen for convenience in a particular case; but for general discussion the useful planes are limited to five in number. They are: (1) the fault plane, itself, *FFFF* in

Fig. 86; (2) the dip plane of the fault, *Df-Df*; (3) the dip plane of the vein, *Dv-Dv*; (4) the plane perpendicular to the trace of

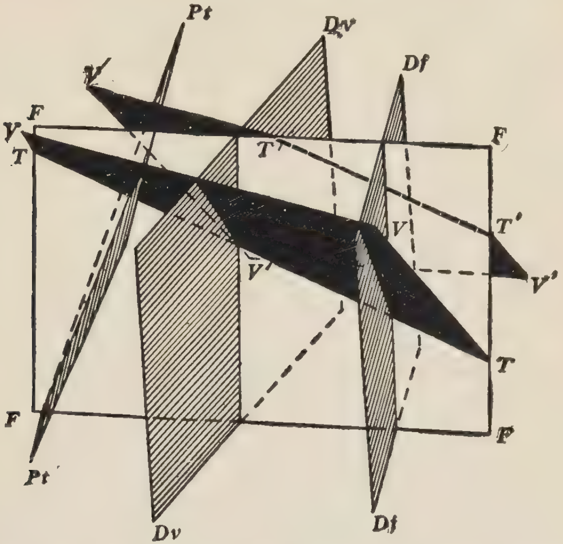

Fig. 86.—Diagram of the planes in which systematic measurements of displacements are made in studying faults.

Isometric projection of an oblique, normal fault. *FFFF* is the fault plane. *VVTT* and *V'T'T'V'V'* are the separated parts of the vein. *TT* and *T'T'* are the traces of the fault plane with the vein.

Three planes are shown cutting across the faulted vein and fault plane. They are *Df-Df*, which is laid at right angles to the strike of the fault and is the dip plane of the fault; *Dv-Dv*, which is laid at right angles to the strike of the vein and is the dip plane of the vein; and *Pt-Pt*, which is laid at right angles to the trace of the fault with the vein.

These three planes, together with the fault plane and a horizontal plane, are those in which the displacements of faults are measured, as is explained in the figures that follow.

the vein with the fault plane, *Pt-Pt*; and (5) the horizontal plane, *NESW*. (Fig. 85).

In order to present clearly the accepted measurements in each of these planes, isometric views of a fault similar to that shown in Fig. 86 have been prepared to present each of the planes to the eye separately and in the foreground. The cube has been turned about and the front of it omitted where necessary to distinctness of the important features. The orientation of the cube can be seen by reference to the letters $NESW$, which stand for the points of the compass and hold a fixed relation to the assumed fault.

Fig. 87 represents an apparently normal, oblique fault, which has displaced a vein by the amount indicated by the distance between TT and $T'T'$, the two traces of the vein with the fault plane. It is assumed that a point V' is represented after faulting at V'' and under that assumption the fault is normal. The line $V'V''$ is in the fault plane and is inclined to the vertical. As assumed it does not lie in the dip plane of the fault. $V'a$, $V''a$, $V'b$, and $V''b$ are lines drawn in the fault plane. They thus lie in one and the same plane with $V'V''$ and they form with that line two right angle triangles.

$V'a$ is in a vertical plane and is the trace of that plane with the fault plane. It corresponds with the dip of the fault. $V''a$ is in a horizontal plane and is the trace of that plane with the fault plane. It corresponds with the strike of the fault. $V'b$ is part of the trace of the vein with the fault plane. And $V''b$ is the trace of the fault plane with a plane which makes a right angle with the trace of the vein and the fault.

Slip is the term adopted by the Committee to designate any component of displacement, measured in the fault plane. Slip may be measured in any direction in that plane, but the components described above are those usually required to analyze a fault movement and they are given special names. $V'V''$ is the net or total slip. $V'a$ is the dip-slip. $V''a$ is the strike-slip. $V'b$ is the trace-slip. And $V''b$ is the perpendicular slip.

The term slip in the sense of a function of displacement measured in the fault plane is excellently selected, and the qualifying terms, net, dip, strike, trace, and perpendicular connote definite relations, so that they are easily understood. They should be generally adopted and used.

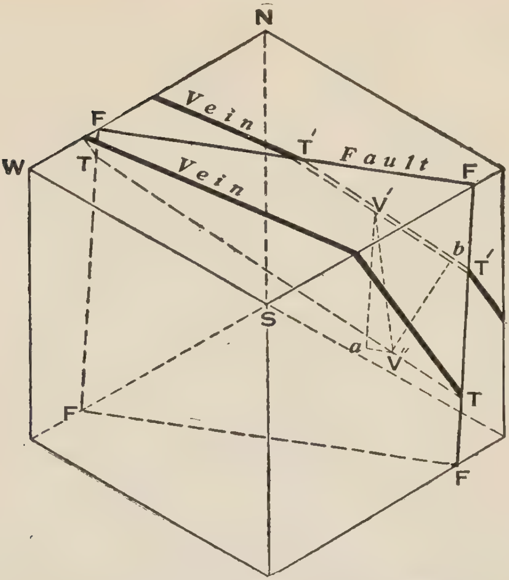

Fig. 87.—View of a normal, oblique fault, looking at the fault plane, *FFFF.*

Displacements.—The displacements of the vein are here shown projected on the fault plane itself. They are variously designated by different authorities as follows:

	G. S. A. Committee	Tolman
$V'V''$	Slip or net slip	Total displacement
$V'a$	Dip-slip	Normal displacement
$V''a$	Strike-slip	Horizontal displacement
$V'b$	Trace-slip	Parallel displacement
$V''b$	Perpendicular slip	Perpendicular displacement

Note.—The term *slip,* which is in common use among miners in referring to any break in the rocks, is given a special meaning by the Committee of the Geological Society, it being used by them to designate movements measured on the fault plane, with the qualifying prefixes given above to distinguish movements, as shown in the figure. Tolman proposed the use of *displacement* for the same measurements and applied the distinguishing adjectives which he uses throughout his logical system of fault nomenclature. In this work we follow the Committee in using *displacement* in the most general sense and employing *slip* for the measurements in the fault plane.

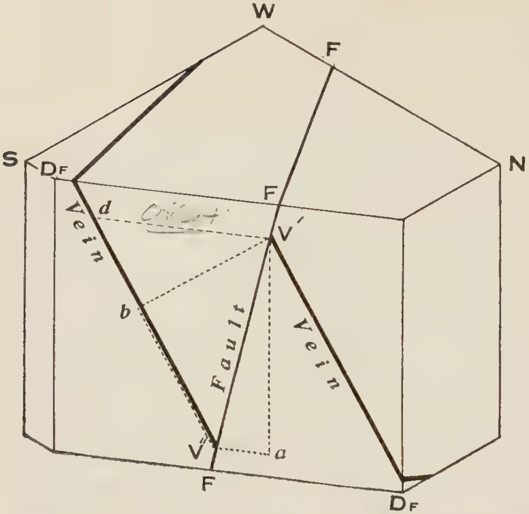

Fig. 88.—View of a normal oblique fault, similar to that shown in Fig. 87, but viewed looking at the dip plane of the fault, that is, at right angles to the view in Fig. 87.

Displacements.—Those displacements measured in the dip plane of the fault are variously designated as follows (see Figs. 87 and 89).

	G. S. A. Committee	Tolman
V'V''	Slip for a dip-slip fault, or apparent slip for an oblique-slip fault	Total throw
V'a	Throw	Normal throw
V''a	Heave	Horizontal throw
V'b	Apparent stratigraphic separation	Perpendicular throw
V''b	No name	Parallel throw
V'd	Apparent offset	No name

Note.—All the above measurements are made in the dip plane of the fault. It will be noted that in this plane lie the throw and heave, as defined by the G. S. A. Committee, whereas the other measurements are qualified as having only the apparent, not the true dimensions. This qualification arises from the fact that the movement on the fault plane may have been in any direction, not necessarily in the direction of the dip-slip.

Tolman adopts the term *throw* for all measurements in the dip plane of the fault and applies the systematic terms that describe the several measurements under his nomenclature.

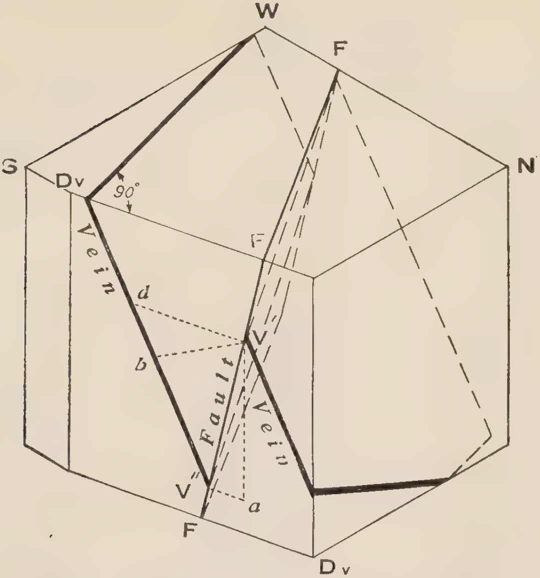

FIG. 89.—View of an oblique fault, similar to that shown in Fig. 87, but viewed looking at the dip plane, *Dv*, of the vein.

Displacements.—Displacements measured in the dip plane of the vein are designated as follows by the G. S. A. Committee. Tolman gave no names to measurements in this plane.

	G. S. A. Committee
V'V''	Apparent slip
V'a	Apparent throw
V''a	Apparent heave
V'b	Stratigraphic separation
V''b	No name

NOTE.—All the possible measurements in this plane, with the exception of the stratigraphic separation, are apparent rather than true measurements of the actual displacements in a given direction, unless the movement on the fault has been parallel to the dip of the vein or strata. This condition would rarely be met with in the case of faulted veins, but may occur where faulting has been directed by the bedding planes of strata. The stratigraphic separation is an important measurement in general geologic work, but is usually of less consequence in mining.

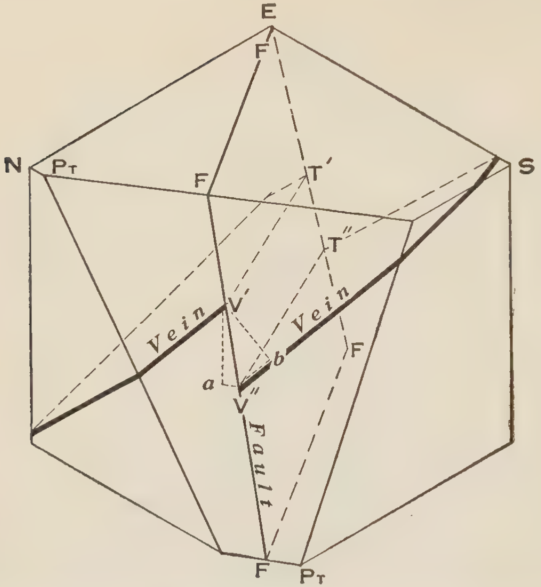

FIG. 90.—View of an oblique fault similar to that shown in Fig. 86, but viewed looking at a plane laid perpendicular to the trace of the vein with the fault plane, *i.e.*, *Pt* in Fig. 86.

Displacements.—Measurements in the plane perpendicular to the trace of the vein and the fault plane are practically confined to mining practice and were not considered by the G. S. A. Committee. Tolman has named them as follows:

	Tolman
V′V″.	Total separation
V′a.	Normal separation
V″a.	Horizontal separation
V′b.	Perpendicular separation
V″b.	Parallel separation

NOTE.—The important measurement in this plane is *V′V″*, the total separation, for it is the shortest distance between the two traces of the vein with the fault plane. Among the other measurements the perpendicular separation is the shortest distance between the two parts of the vein and is the same as the stratigraphic separation as defined by the G. S. A. Committee. (Fig. 89.)

Spurr had previously suggested the use of " throw " for $V'a$ and " lateral separation " for $V''b$. Tolman employed " displacement " in the specific sense in which the Committee uses " slip " and, recognizing the five special measurements, called them " total, normal, horizontal, parallel, and perpendicular displacements." Thus in his terminology " normal " corresponds to " dip," *i.e.*, measured in a vertical plane; " horizontal " to " strike "; and " parallel " to " trace " of the Committee's terminology.

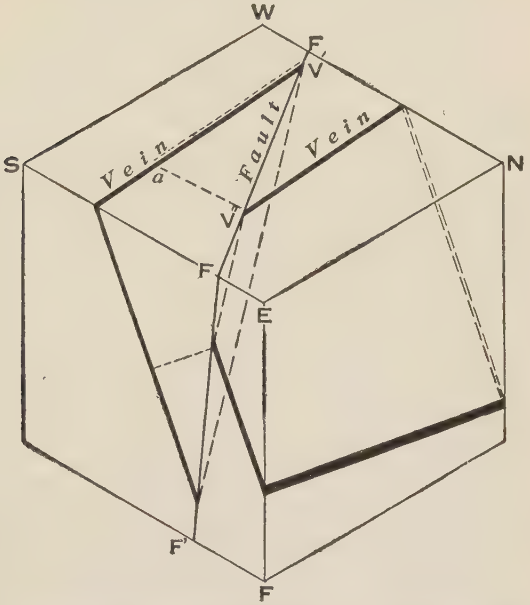

FIG. 91.—Fault Measurements in a Horizontal Plane.

	G. S. A. Committee	Tolman
$V'V''$	Strike-slip	Total heave
$V''a$	Offset ("Heave," Geikie)	Perpendicular heave
$V'a$	Overlap *	Parallel heave.

* Called " Gap " in case there is a space between V' and V'' in which the vein is missing.

CHAPTER VI

STRUCTURES OF IGNEOUS ROCKS

Igneous rock masses classified and described. Extrusives discussed with reference to the manner of their eruption and the cones, flows, and lava fields they form. Their internal structures described. Intrusives classified according to the forms which the masses assume. The structures imposed upon the masses by cooling and by pressures which may subsequently affect them discussed.

EXTRUSIVES

Forms of Extrusives.—Those eruptive rocks which reach the surface of the earth are classed as extrusives. They may erupt in a molten state and may build up dome-like volcanos such as Mauna Loa in the Hawaiian islands, or lava streams, or lava fields; or they erupt explosively and form cinder cones, volcanic mud flows, and ash beds.

Volcanic cones of notable size are composite structures, being made up of the products of many eruptions. Lava flows and beds of cinders usually alternate in the pile. Where ravines are cut they exhibit walls of cliffs and benches, and may frequently be occupied by new lava streams. The central throat is filled with lava which congeals there, and dikes extend out from the throat or rise from deeper sources. The mountain forms which erosion sculptures from these complex structures by removing the softer masses and exposing the ribs are among the most picturesque and offer an interesting subject of structural study. They have little relation, however, to anything but the development of the individual volcano.

Lava flows from volcanos take the lowest available channel and may extend to considerable distances. Occupying a river valley a flow buries the gravels and causes the tributary streams to gather along either side, forming twin rivers. In time the latter may sink their canyons deeply and isolate the buried gravels and the lava flow as a high ridge. This has been the history of the auriferous gravels of the Sierra Nevada of California.[1] This is but one illustration of the influence of lava flows upon the arrangement of streams and superficial structural features. They frequently dam rivers and form lakes. The latter may overflow into another water shed and complete changes of river systems may result.

Lava fields are extensive areas covered by lava. As a rule the lava has not been erupted from volcanos but from innumerable fissures, and has spread like a flood.[2] The Snake River lava fields, the largest in North America, cover about 100,000 square miles. The Dekkan trap area in India and the great lava fields of South Africa are similar eruptions. They all consist of basalts. The thickness of lava as exposed in the Snake River canyon is about a mile. The total volume of the field is therefore very great. It is made up of many distinct sheets, each one of which has spread out over the earlier ones, having risen through them in the form of dikes. The whole mass is therefore bedded and from the point of view of a structural element of the region it resembles a very extensive horizontal stratum which may be folded or faulted.

Explosive eruptions occur in consequence of the extrusion of steam from crystallizing lava, in such manner that the rock is blown to pieces and forms cinder or ash. Blown out into the air, it may fall back around the orifice and build up a cinder cone; or it may mingle with the condensing steam to form a mud-flow which then behaves like fluid lava; or it may be spread by winds and fall as a sheet of ash. If encountered in the course of structural studies these individual formations are of interest in themselves, especially as key rocks or definite time markers, but they have little bearing on broader relations.

Original Structures of Extrusives.—Rapid cooling fixes in lavas the lines of flow which are produced during their movements, and thus preserves the characteristic fluidal or flow structure of the glassy state. Crystallization destroys this structure.

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[1] LINDGREN, WALDEMAR, The Tertiary Gravels of the Sierra Nevada of California. U.S.G.S., *Prof. Paper* 73, 1911.

[2] RUSSELL, I. C., "Volcanos of North America," pp. 36–43, 1897.

When lavas cool somewhat more slowly they crystallize and develop characteristic internal structures due to shrinkage of volume. Some lavas pass through a pasty state, and these acquire only very imperfect block structures. Others, particularly the basalts, pass quickly from the highly fluid state to the solid crystalline condition and then cool down. The pronounced shrinkage of volume establishes a state of tension in response to which the rock separates into well-developed plates or into jointed columns.

The process is easily visualized. The cooling mass at any stage is coolest at the outer surface and hottest within. Between the two extremes we may imagine any number of ideal surfaces of equal temperature, isothermal surfaces. Shrinkage takes place at right angles to the isotherms and tends to pull the rock apart in a direction parallel to them at spaces determined by the amount of shrinkage and the degree of cohesive strength of the rock. If the shrinkage is relatively great the division will be into thin layers that imbricate one with another and take up the lateral shrinkage by slipping on each other. The rock then readily breaks into thin, ringing plates or shells; it is said to have a platey structure.

If the tension is less intense the parting surfaces parallel to the isotherms are more widely spaced and may be from one to several feet apart. Lateral shrinkage then divides each thick layer into columns, which would tend to assume hexagonal cross-sections but more often are of pentagonal or quadrilateral shape because of unequal pressures and tensions in the cooling mass. The columnar structure thus developed is peculiarly characteristic of basalt and is sometimes called *basaltic* structure. Well-known examples are seen in Fingal's cave on the Scottish coast, in Yellowstone Park, along the Columbia River Highway in Oregon, and elsewhere wherever thick flows of basalt occur.

The conditions of columnar development in consequence of cooling fix the positions of columns at right angles to the cooling surface. They usually stand, therefore, in a more or less nearly vertical position. But if the cooling surface is curved the forms assume a radial position. This is likely to occur in the interior of a flow, around a residual molten portion, the last to consolidate.

The vertical columnar structure in extensive basalt sheets has certain important results in relation to water supply and landslides. The columns readily spread apart and admit rainfall to the mass. Water is therefore scarce on the surface but is apt to issue as large springs or underground streams at the contact of a lava flow with any underlying impervious layer. The reservoir capacity of the fissures is large; the delivery is gradual; and the volume of flow is correspondingly steady.

The columnar structure maintains cliffs along the sides of canyons cut in basalt. It also weakens the lava sheet and facilitates vertical parting when a section tends to slide on a wet base. The weight of basalt promotes movement. Landslides are therefore common where extensive basalt flows are trenched.

Deformation of Extrusives.—Lava flows, because of their bedded character formed by the spreading out of successive sheets one above the other, partake to some extent of the structures of sedimentary rocks, and may be flexed or folded. The interpretation of dips in lava flows is complicated by the fact that they may solidify from the molten state at a considerable angle from the horizontal. Any consideration of tilted lavas should therefore take account of the location of the centers of eruption, the type of lava, whether acidic or basic (as the latter has greater fluidity and is less apt to solidify on a steep slope) and also of the relation of the supposed structures of deformation to the tectonic lines of the region, in order to determine whether the forces which deformed the surrounding area could have produced the observed structures of the lava flows.

INTRUSIVES

Forms of Intrusives.—Five forms of intrusive igneous bodies are readily distinguished: *dikes*, *sills*, *laccoliths*, *stocks*, and *batholiths*.

Dikes are thin bodies of molten magma intruded into fissures. On solidifying they resemble a wall dividing the rock mass into which they have penetrated. When exposed by erosion they remain standing above the surface, like walls.[1] Dikes are thin in one horizontal dimension, often very extended in the other, and of indeterminate depth as a rule. They usually rise from some deep-seated body of magma, either a larger intrusive mass or the hearth of a volcano. They are sometimes exceedingly numerous, as in the case of the feeding dikes of a large lava field, and then constitute a notable proportion of the horizontal extent of the intruded area. In such cases they are practically vertical, but they may assume any attitude toward the horizon, though their inclination is usually steeper than 45 degrees. Dikes may intersect one another, may branch, and may develop into irregular bodies (*apophyses*).

A sill is a sheet of magma intruded between sedimentary strata in such a manner that it extends parallel to them and appears to constitute a member of the conformable stratified series. Its thickness is commonly a few feet or tens of feet, while its area may be many square miles. A lava flow, if poured out on the sea bottom and spread over marine sediment and subsequently covered by sediment, would resemble a sill, but there would be characteristic differences of metamorphism in the adjacent strata by which the one case could be distinguished from the other.

A laccolith is a mass of magma which in rising forces itself in between strata and lifts those that are above it, so that they form a dome. Laccoliths and sills are related forms, both being intruded between sedimentary beds. But they are distinguished by the greater thickness of the laccolith and the arching of the strata over the igneous mass. The bottom of a laccolith corresponds with the strata through which the magma has risen and is flat. The top is arched like the overlying strata, but the igneous rock extends out in dikes or other offshoots from the main body. The plan of a laccolith is generally rounded but more or less irregular. Laccoliths were first described by G. K. Gilbert,[1] and have been discussed by Whitman, Cross [2] and T. A. Jaggar.[3]

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[1] Spanish Peaks Folio. U. S. Geological Survey, Geologic Atlas of the United States, Folio No. 71, 1901.

A stock is an irregular body of intrusive rock that has an indefinite vertical dimension, rising as it does from below, but is relatively small and irregular in horizontal diameters. It occupies a group of fissures in the country rock, presenting a central column with many branches. In many cases stocks fail to reach the surface and are exposed only by denudation. In other cases the upper part of a stock may be represented by a volcanic neck, the lava which solidifies in the throat of a volcano.

Batholiths are large masses, commonly of granite or granodiorite, intruded from greater depths into rocks some thousands of feet below the surface. The body may comprise many thousand cubic miles, all of which was apparently molten at one and the same time and cooled during the same geologic epoch. The forms of these deep-seated and therefore hidden masses have been the subject of much speculation.[4] It is known that the upper surface is usually broad and carries large fragments of the country rock in which the granite was intruded (*roof pendants*). The lower surfaces of a batholith have been variously delineated: as though it were a bulky, flat-bottomed mass, or a huge pear bulging at the top, or an enormous dike with a flat, spreading top. The trend of opinion now inclines toward a limitation in the size of batholiths, and it is reasonable to infer that there are many forms of these intrusions which vary according to the conditions of pressure and resistance that governed at the time of their rise into the outermost crust of the earth. Without attempting at present to analyze these conditions, regarding which we may reason but which we cannot observe, we may call attention to the different shapes suggested by the different outlines of batholiths, as shown on maps of different areas.[1] Along the Pacific coast the granodiorite batholiths of Lower California, California, and British Columbia are long and narrow. They are relatively young intrusions (Mesozoic and Tertiary) which conform to the older outline of the continent and to the excessive pressure that has been exerted in a zone many miles below the surface between the sub-oceanic rocks and the continental mass. In the interior of the continent ancient granites make up the larger part of the Laurentian shield and similar continental nuclei or *positive elements.*[2] The granite is intruded into metamorphic rocks of all kinds and it appears in dikes as well as in very large masses. The latter are rounded in form and suggest that they spread out laterally as the intrusive mass approached the surface of the earth long ago. Experiments by R. T. Chamberlin [3] on the forms of intrusion indicate the development of a " tack-shaped " form which is peculiarly appropriate to this type; but the points of the tacks may well be replaced by many intersecting dikes, and the batholiths may be comparable to those great basalt flows which are erupted through innumerable fissures. There is a difference in habitat, however, since the basalt erupts and spreads on the surface, whereas the granitic magma, if it solidifies as granite, does not reach the surface.

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[1] GILBERT G. K., Report on the Geology of the Henry Mountains, (Utah). U. S. Geog. G. S. of the Rocky Mts. (Powell), 1877.

[2] CROSS, C. W., The Laccolitic Mountain Groups of Colorado, Utah and Arizona. U. S. G. S. *Ann. Report* 14, pt. 2, pp. 157–241, 1894.

[3] JAGGAR, T. A., The Laccoliths of the Black Hills, U. S. G. S. *Ann. Report* 21, pt. 3, pp. 163–290, 1901.

[4] DALY, R. A., "The Origin of Igneous Rocks," 1914.

Continental and Oceanic Structures.—The preceding comparison suggests a difference of structure which probably distinguishes continents from ocean basins. The trend of modern evidence from seismology, that is from the study of earthquake waves, is to show that where there are continents the outer skin of the earth, a shell 30 miles or more deep, is composed chiefly of granite or other acidic igneous rocks; whereas, beneath the ocean basins basalt or similar basic rocks predominate. Attention is thus directed to the separation of large masses of granitic magma from even larger masses of basaltic magma, and the problem of the origin of continents and ocean basins is seen to involve the origin and differentiation of igneous rocks in general. Experimental investigation demonstrates that granite will crystallize out in basic magmas. It is inferred that it has done so on a large scale in the earth's interior and that continents have developed where large intrusions of granite approached the surface. The suboceanic crust, on the other hand, appears to consist of great outflows of basalt, each one of which has been erupted through older flows and has spread out over them.

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[1] Geologic Map of North America, U. S. Geol. Survey, 1910.

Geologic Map of Canada, James White, Cartographer; *Atlas of Canada*, Map No. 4, Dept. of Interior of Canada, 1906.

[2] Willis, Bailey, Hypothesis of Continental Structure; *Bull.* Geological Society of America, 1907.

[3] Chamberlin, R. T. and Link, T. A., The Theory of Laterally Spreading Batholiths. *Journal of Geology*, vol. XXXV, No. 4, 1927.

Original Structures of Intrusives.—Like the extrusive rocks, intrusives are subject to the stresses set up by contraction on cooling. Dikes and sills, being tabular bodies, may show jointing similar to the jointing in lava flows. Platey structure parallel to and near the cooling surface may be found in either, though in intrusive bodies it is apt to be " blind " and brought out only by weathering. Columnar structure similar to that found in basaltic flows, is found in basic sills, as in the case of the Palisades of the Hudson, in New Jersey.

The larger forms of intrusives present a different problem, as the surfaces of cooling are usually remote from the locus of the final solidification of the mass, and as the bodies are irregular in shape. Further complications result from the differentiation of the magma into rocks of different physical constants. The final stages of cooling in a batholith may produce most complex structures, however, though it is difficult to distinguish between those formed strictly by cooling and those formed by later deformation. Complex joint systems and faults of considerable magnitude may be developed within batholiths where there is no adequate evidence of external pressure, and where dikes and veins along the fissures indicate that they were formed while other portions of the body of magma were still liquid. The classic example of this type of fissuring and faulting is that of Butte, Montana. The extremely detailed geologic study of the veins and faults of the great copper mines has revealed six sets of fissures, on some of which displacements up to two or three hundred feet have occurred. The effect seems to be the result of cooling combined with torsion in the part of the batholith where the final differentiates were segregated and were solidifying. There is a fault of regional magnitude east of the district, an up-thrust with a throw of 1,500 feet; but this is not mineralized, hence it is presumed to be later than the fissuring in which the mineral-bearing veins were deposited.

Deformation of Intrusives.—Intrusive masses, like all of the rocks in the earth's crust, are subject to deformation by external forces. All forms may be sheared or fractured, producing joints in sets which are related to the regional deformation, rather than to conditions of cooling. Sills, like lava flows, may be folded with the sediments into which they are intruded.

The structures imposed on batholiths by external forces are those which would be expected in great homogeneous masses, namely flow structures and shear structures. Flow structures involve recrystallization and produce metamorphic phases. Because of their rigidity, batholiths are important agents in controlling the deformation that takes place in the rocks surrounding them. They act as buttresses, and lines of folding and of shear and flow curve around their margins concentrically. A study of their form, therefore, is frequently of great importance in interpreting structures found beyond their limits. An example may be found in the great San Andreas fault of California, which is regarded by Bailey Willis as a shearing plane developed between the batholith of the Sierra Nevada and that of Lower California in its northern extension.

CHAPTER VII

STRUCTURES OF METAMORPHIC ROCKS

Cleavage; cleavage and splitting distinguished; conditions of cleavage as defined by Van Hise and confirmed by Leith. Classification; discussion of fracture cleavage and flow cleavage. Relations of cleavage to stratification and folding. Significance of cleavage in structural relations, as defined by Dale. Cleavage and flow; Heim's contribution to the subject (1878). Van Hise's analysis of flow. Mashing, shear flow, pure shortening, and melting; these are modes of flow found in rocks deformed under different conditions of stress at different depths.

CLEAVAGE

Definitions.—To split or to cleave are English synonyms with a slight difference of meaning which leads us to say that a rock cleaves rather than that it splits. The word *cleave* carries the idea of parting along a flat, smooth surface, the characteristic parting of rocks. Split admits of the same interpretation, but is not so definitely limited to a plane parting. Hence we speak of rocks cleaving rather than splitting and use the noun *cleavage* rather than split.

Cleavage in rocks has been studied by many eminent investigators, beginning with Sedgwick in 1829, but it was not until Van Hise and Leith carried out their exhaustive studies that the complexities of the phenomena were unraveled. Van Hise published his results in several papers[1] and was followed by Leith[1] after ten years more of thorough investigation.

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[1] VAN HISE, C. R., Principles of North American Pre-Cambrian Geology, U. S. Geol. Surv., *Sixteenth Annual Rept.*, pt. 1, pp. 633–668, 1896. Deformation of Rocks, pt. 3, Cleavage and Fissility, *Jour. Geol.*, vol. IV, pp. 449–483,

These researches may be regarded as having established beyond question the conditions that determine rock cleavage.

Van Hise states them as follows:[2]

> Rock cleavage is due to the arrangement of the mineral particles with their longer diameters or readiest cleavage, or both, in a common direction, and this arrangement is caused: first and most important, by parallel development of new minerals; second, by the flattening and parallel rotation of old and new mineral particles; and third and of least importance, by the rotation into approximately parallel positions of random original particles.

The validity of this statement was confirmed by Leith,[3] who amplified the explanation of the conditions governing cleavage as follows:

> In the rocks with secondary flow cleavage examined during this investigation, which are believed to be fairly representative of such rocks in general, a plane, or surface of cleavage has been observed to be uniformly parallel to the greatest and mean, or greatest and least dimensions, or both, or even to the greatest alone, of the parallel constituent mineral particles. This has been observed macroscopically in thousands of specimens, and microscopically in several hundred prepared slides. Not only has a cleavage been observed to coincide with the longer diameters of the parallel particles, but it has been apparent that the excellence of such cleavage is proportional to the degree of the arrangement and to the inequality of the dimensions of the particles. In addition to this essential condition of parallel arrangement, another condition, dependent on the first, has been observed to be of great importance—the parallel ar-

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1896. Metamorphism of Rocks and Rock Flowage, *Bull.* G. S. A., vol. 9, pp. 269–328, 1898. A Treatise on Metamorphism, U. S. Geol. Surv., *Mon.*, vol. 47, pp. 748–763, 1904.

[1] LEITH, C. K., Rock Cleavage, U. S. Geol. Surv., *Bull.* 239, 1905.

[2] VAN HISE, C. R., Principles of North American Pre-Cambrian Geology, U. S. Geol. Surv., *Sixteenth Annual Report,* p. 635, 1896.

[3] *Op. Cit.*, p. 49.

rangement of mineral cleavages. This has usually aided the dimensional arrangement, but has rarely tended to cause a cleavage in a plane different from that caused by the dimensional arrangement of the mineral constituents.

It is apparent that certain minerals, possessing the quality of breaking or crystallizing in flat or elongate forms, will more perfectly produce cleavage than others whose habit of form is rounded. It is also true that minerals tend to develop in harmony with their dynamic environment. Therefore, if it were possible for either one of several minerals to develop at a given point and the pressures at that point favored the growth of flat or elongate minerals, they would be the ones that would form and they would give rise to cleavage. Rock cleavage is thus related to a few minerals, which Leith enumerates as the constituents of the bulk of cleavable rocks. He says:

> The micas, including muscovite and biotite, chlorite, hornblende, quartz, and feldspar, are in greatest abundance, making up, perhaps nine-tenths of them. Other minerals, characteristic though less abundant, are calcite, tremolite, actinolite, garnet, tourmaline, staurolite, chloritoid, sillimanite, etc.

The dynamic conditions under which these minerals might develop in such a way as to produce a cleavable rock have been the subject of much discussion. Van Hise and Leith made a fundamental contribution to the knowledge of the phenomena by demonstrating that there are several kinds of rock cleavage and that they differ in the conditions of their origin. They classified rock cleavage accordingly, and Leith[1] finally threw the classification into the following form:

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[1] *Op cit.*, p. 12.

Classification of Cleavage

(According to Van Hise and Leith)

- Rock-cleavage. (Cleavable rock.)
  - *Original cleavage.* (Protoclase or original cleavage rock.)
    - Bedding.
    - Flow structure in lavas.
    - Parallel structure in certain gneisses.
    - Pegmatitic structure.
    - Parallel structure due to the arrangement of feldspars in certain gabbros, etc.
  - *Secondary cleavage.* (Metaclase or secondary cleavage rock.)
    - *Flow cleavage.* Including in whole or in part:
      - " Ultimate cleavage " of Sorby, "Cleavage" of most writers, "Slaty cleavage," "Cleavage proper," etc.
      - Schistosity. (Schists.)
      - Slatiness. (Slates.)
      - Parallel structure in certain gneisses. (Comes partly under schistosity.)
    - *Fracture cleavage.* Including in whole or in part:
      - Close joints cleavage.
      - False cleavage.
      - Strain slip cleavage.
      - Ausweichungs cleavage.
      - Fissility in part. (The term is retained for closely spaced, parallel partings.)
      - Rift.

The preceding classification of cleavage is the result of a very comprehensive study, extended over twenty years and intensified by controversy. It comprises, therefore, all possible structures to which the term cleavage can be applied and more than are usually included under that term. Thus, bedding and flow structure in lavas are not called cleavage, although the rocks possessing these structures have a capacity to part along parallel surfaces. Certain gneisses, on the other hand, exhibit an original arrangement of minerals in parallelism which results in original cleavage. They and similar originally cleavable, crystalline rocks may properly be called *protoclase.*

In general, the term cleavage covers only the secondary structures, those which are a result of recrystallization or of shearing of the rock subsequent to its original consolidation. Such rocks fall into the class of the *metaclases*.

Attention may well be concentrated on the distinction between fracture cleavage and flow cleavage, which is stated by Leith as follows:

> *Fracture cleavage* is conditioned by the existence of incipient, cemented, or welded parallel fractures, and is independent of a parallel arrangement of the mineral constituents. *Flow cleavage* is conditioned solely by a parallel arrangement of the mineral constituents.

The importance of this distinction lies in the relation which the direction of the cleavage bears to the major force affecting the rock mass at the time of the development of the structure, whichever it may be. For the complete discussion reference should be made to Leith's presentation. It has been held by some that all cleavage developed in a direction at right angles to the major pressure, whereas it was maintained by others that all cleavage grew in a plane inclined to that pressure. According to the former, the direction of cleavage represented the normal plane, whereas according to the latter it represented a shearing plane.

Van Hise demonstrated that there is a cleavage developed in the normal plane, which he called "flow cleavage," and that there is a different kind of cleavage that develops in the shearing planes, to which he and Leith finally gave the name "fracture cleavage." The recognition of the two great classes, characterized by distinct features and bearing different relations to the direction of the major pressure at the time of their growth, was a definite advance.

Subsequent studies have, nevertheless, led Leith to recognize that the distinction between cleavage developed at right angles to the major pressure and that developed parallel to shearing planes inclined to the major stress cannot be established in many cases. He expressed this view as follows:[1]

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[1] Leith, C. K., The Structural Failure of the Lithosphere. *Science*, vol. LIII, p. 198, 1921.

The interpretation of rock cleavage or schistosity, a common though not the only evidence of rock flowage, affords an especially good illustration of the danger of using narrow assumptions as to its relations to causal stresses. Cleavage is a capacity to part along parallel surfaces determined by the parallel dimensional arrangement of mineral particles. There is abundant proof that the schistose rock has been elongated parallel to the cleavage surface, and cleavage thus becomes evidence of elongation. It does not follow, however, that the stress producing elongation was applied normal to it.

The further discussion of the mechanical conditions of rock shear is deferred to another chapter (page 225). We here take up its relations to other structures, such as stratification and folding.

Secondary cleavage is independent of bedding. Already in 1835 Sedgwick[1] stated this fact from his observations in the mountains of north Wales. He wrote:

> The whole system of slates and tabular porphyries has been thrown into a number of great undulations, producing through the chain a series of longitudinal anticlinal and synclinal lines. Parallel lines of cleavage not merely affect given beds, but sometimes run, without deviation, even through coarse mechanical subordinate strata, affecting whole ranges of mountains and preserving their parallelism in spite of undulations and anticlinal lines.

Sedgwick's observation has been confirmed by many observers. Regional cleavage or schistosity maintains its course independently of the strike of the stratification in folded strata. Heim [2] formulated a law of parallelism between the strike of strata and that of cleavage, but it is to be noted that the folds of the Alps which he studied were so closely compressed that the strikes of the strata are parallel to the axes of the anticlines and synclines. Now cleavage does run parallel to the axes of the folds, as he also observed, and therefore parallel to the strike of the bedding where compression has been excessive, but, remaining parallel to the axes, it cuts across the strata where they strike at an angle to the axes, as they do in open pitching folds.

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[1] SEDGWICK, ADAM, Remarks on the Structure of Large Mineral Masses, etc., *Trans.* Geol. Soc., London, second ser., vol. 3, pt. 1, pp. 461–468, 1835.

[2] HEIM, ALBERT, "Mechanismus der Gebirgsbildung," p. 68, 1878.

The relation of cleavage to stratification in folded regions is of first importance as a guide to structures that may often be obscure. Dale [1] has stated the facts very clearly, and we quote his summary, with the reservation, however, that it was written as applying to a specific case and that the particular conditions might vary in other localities. He says:

> The rocks are all metamorphic and of few kinds, crystalline limestone, quartzite, and schists. The key to the structure is in the distinction between cleavage foliation and stratification foliation. The phenomena, as they occur on Mt. Greylock, involve cleavage, stratification and pitch of the axes of folds in a manner which led to the adoption of the following structural principles: I. Lamination in the schist or limestone may be either stratification foliation or cleavage foliation or both, or sometimes, in limestone at least, false bedding. To establish conformity (between strata) the conformability of the stratification foliation must be shown. II. Stratification foliation is indicated by: (*a*) the course of minute but visible plications (this criterion would fail in the case of cleavage foliation having been plicated, as happens in more intense or repeated folding); (*b*) the course of microscopic plications; (*c*) the general course of the quartz laminæ whenever they can be distinguished from those that lie in the cleavage planes. III. Cleavage foliation may consist of (*a*) planes produced by or coincident with the faulted limbs of the minute plications; (*b*) planes of fracture, resembling joints on a very minute scale, with or without faulting of the plications; (*c*) a cleavage approaching slaty cleavage, in which the axes of all the particles have assumed either the direction of the cleavage or one forming a very acute angle to it, and where stratification foliation is no longer visible. IV. A secondary cleavage, resembling a minute jointing, occurs in scattered localities. V. The degree and direction of the pitch of a fold are often indicated by those of the minor plications on its sides. VI. The strikes of the stratification foliation and cleavage foliation often differ in the same rock, and are then regarded as indicating a pitching fold. VII. Such a correspondence exists between the stratification and cleavage foliations of the

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[1] DALE, T. N., Mount Greylock, Its Areal and Structural Geology, U. S. Geol. Surv., *Mon.* XXIII, pt. 3, p. 125, 1894.

great folds and those of the minute plications that a very small specimen properly oriented gives, in many cases, the key to the structure over a large portion of the side of a fold.

It is to be observed that the cleavage described by Dale is that which Leith calls "fracture cleavage" in distinction to flow cleavage. Such cleavage in some cases develops after the manner of minute thrust faulting in the overturns of the tiny plications; that is to say, in the process of shearing that portion of the rock mass involved between the two passing limbs of a very small or microscopic fold. Again, there may be no apparent folding, even of microscopic dimensions, but displacement occurs on a plane of shear. And in related cases, where the recrystallization has gone far enough to produce a growth of mineral particles, oriented in parallelism, either as they formed or by rotation in the progress of the movement, the fracture cleavage partakes of the essential character of flow cleavage. This type of cleavage was distinctly recognized and described by Heim as "ausweichungs clivage." (Figs. 29 and 30.)

The most useful items in Dale's descriptions relate to the distinction of stratification and cleavage in foliated rocks, and further to the use of minute plications as indices to the character of the major structures.

HOW ROCKS FLOW

Heim was the first to recognize and clearly state that solid rocks can flow. In his work on the mechanics of mountain building[1] more than half a century ago he wrote:

> In the intimate examination of many folded or squeezed strata veins and open fractures are so rarely to be observed that we can not possibly ascribe the deformation to that kind of displacement. Even in the most brittle rocks we discover the most complete bends without a trace of fracture connected with them. In addition to the bends without breaks there are many other evidences that in general in connection with moun-

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[1] HEIM, ALBERT, "Mechanismus der Gebirgsbildung," II. Teil, Algemeine Untersuchungen, Seite 31, 1878.

> tain building the molecules of rocks, even of the most brittle, may be displaced like those of plastic masses. . . . Bending, stretching, thickening, rolling out, and shearing are commonly related to one another. . . . Deformation without fracture is an effect of higher mechanical stresses than deformation with fracture.

Van Hise, through his exhaustive microscopic studies of pre-Cambrian rocks, obtained a most intimate knowledge of rocks that had flowed, and he was able greatly to extend and confirm the observations of Heim. His views have become the basis of our understanding of metamorphism and are widely quoted.[1] He introduced the terms *mashing*, and *zone of flowage*, which have come into general use. Leith has carried on Van Hise's studies and has reduced the enormous volume of data which the latter assembled to convenient form in his two textbooks.[2]

Rocks flow in four different ways according to their own properties and the conditions of their environment. The four modes are: mashing, shear flow, pure shortening by recrystallization, and melting. We will briefly consider the conditions that govern each of these modes of flow.

Mashing.—Van Hise, writing at the time when the facts of observation were fresh in his mind, described the meaning of his own term very clearly:[3]

> "In the treatment of folding, cleavage, and fissility it has been shown that layers are deformed by plastic flow, by fracture, and by accommodations between them, . . . (as well as by) rearrangement within the beds themselves. . . . This deformation may be partly accomplished by rearrangement of the mineral particles with reference to one another. The process may go so far as to much flatten the grains by flowage or to produce peripheral or entire granulation of the individual original grains. . . . Not only may all the minerals and combinations of minerals thus be flattened by flowage or granulation, but the resultant layers or particles may be intermingled to some extent, and thus we may have laminated or

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[1] Van Hise, C. R., Principles of North American Pre-Cambrian Geology, U. S. Geol. Surv. *Sixteenth Annual Report*, pp. 634, 694 et seq., 1896.

[2] Leith, C. K., "Structural Geology," revised edition, 1923.

Leith, C. K. and Mead, W. J., "Metamorphic Geology," 1915.

[3] *Op. cit.*, p. 694.

foliated schists. . . . If the original rock was a conglomerate and the metamorphism is complete, each pebble makes a lamina of a different kind from those adjacent and thus gives the rock a banded character.

It is clear from this description that Van Hise included under mashing those mechanical effects that are produced where rocks crush minutely, and also change of form by molecular rearrangement. Minute crushing requires excessive stresses as compared with the strength of the rock. It means that the interstitial spaces are also minute or microscopic. Granulation, therefore, is a mode of deformation that develops in deeply buried rocks. The experiments of Frank Adams, which are described in Chapter XVIII, demonstrate the degree of unbalanced pressure necessary to crush minerals under great confining pressure and indicate that the load must be equivalent to that which rocks carry at the depth of 30 miles (48 kilometers) below the surface. It does not follow, however, that any rocks which we may observe to have been mashed have been so deeply buried. At much shallower depths local pressures may develop intense stresses that rise to the degree indicated, and mashing probably may occur anywhere below the zone of open fractures, say below 3 to 5 miles (5 to 8 kilometers), provided the opposed stresses are adequately concentrated and take effect before other adjustments can be reached.

The changes of form by molecular rearrangement which are associated with crushing are results of recrystallization and are effects of chemical affinity promoted by heating. In relatively shallow zones they occur where work is done by intensified stress and they are more fully developed in connection with shearing.

Shear Flow.—When a rock mass is forced to shear under great confining stress the shearing planes tend to be very closely spaced and the displacements on the very numerous planes are individually small, even though their total may be large. The effect upon the rock is that of flow confined to a thinner or thicker layer. The microscopic changes include granulation and molecular rearrangement. The mode of deformation is therefore by mashing, but it is a special case in which the concentration of stress is on the shearing planes.

Becker attributed all cleavage to recrystallization on shearing planes and deduced the corresponding direction of compression, at 45 degrees to the planes of shear.[1] Van Hise took issue with this conclusion. He designated cleavage developed on shearing planes as " fracture cleavage " to distinguish it from cleavage developed on planes normal to the stress, which he called " flow cleavage." The distinction is very important in analyzing the conditions of stress to which a particular occurrence of cleavage should be attributed, but the nature of the deformation is often similar in the two cases and the names assigned them are misleading, since " fracture " cleavage often involves flow.

It is held by many geologists that pressures in the zone of flow are transmitted "hydrostatically" and are, therefore, not directed into shearing planes. This mistaken assumption leads to the erroneous conclusion that shearing does not occur in the zone of flow and that cleavage on shearing planes could not develop in that zone. In discussing the manner of behavior of overloaded rocks (Chapter XVIII) it is shown that they do shear. It follows that the rearrangement of minerals on shearing planes must take place, especially since the conditions favor flow of the rock. Thus shear flow may be regarded as a mode of deformation in rock masses at great depths; presumably it is a form of localized deformation in solid rock at all depths below the uppermost zone of fracture.

Shearing involves work and work produces heat, which in a confined position raises the temperature of the substance that is sheared. Shearing under great confining pressure becomes so intimate that it extends to the molecules and weakens their bonds among themselves. The rising temperature assists the molecular disintegration and melting is apt to result on shearing planes, in consequence of these conditions. Thus shear flow may take place in different ways in different zones. In the zone of fracture it may occur with pronounced crushing and granulation. In the deeper parts of the zone of fracture there may be less granulation and more molecular rearrangement. In deeper zones or on shearing planes at less depths, where high temperature is locally developed, shear flow may occur entirely through recrystallization and it may even involve local melting in the zone of shear. In the latter case the friction opposed to shear will be relieved by the lubricating effect of the molten rock, and displacement will be greatly facilitated.

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[1] Becker, G. F., Finite homogeneous Strain, Flow, and Rupture of Rocks. *Bull.* G. S. A., vol. IV, pp. 22–25, 1891.

Pure Shortening.—Under the heading Development of Cleavage in Homogeneous Rocks Van Hise says:[1]

> It is my conviction that a structure develops in the normal planes (perpendicular to the major stress) in certain conditions, and that under other conditions structures develop in the shearing planes, as advocated by Becker. The first is believed to be a deep-seated phenomenon of the zone of flowage; the second is believed to be a more superficial phenomenon in the zone of fracture. . . . Rocks when deformed under great weight flow as a plastic solid and under these circumstances the property of cleavage is developed. . . . If the force be so applied that there is uniform shortening in one direction, as in the case of a rigid piston, the elongation is at right angles to the direction of thrust or in the normal planes. This may be called *pure shortening*. (It is a) particular kind of nonrotational distortion. The volume remains unchanged, the shortening in one direction being compensated by equivalent elongation at right angles to this. In this kind of deformation, while there is no differential movement or shearing in the normal planes, shearing does occur along all of the intersecting diagonal planes.

While, as stated above, we differ from Van Hise in that he limits the development of shear flow (Becker's interpretation) to a relatively superficial zone and we do not, there is no question about the development of cleavage in the normal planes and it is what Van Hise and Leith have called " flow cleavage."

The conditions of development of flow cleavage have been stated in preceding paragraphs. The result is a parallel arrangement of minerals, on account of which the rock parts readily in one direction. The structure is produced under conditions that are favorable for the solution of those minerals that are not adapted to their stress environment and the formation of those that are. The latter lie with their longer axes in the direction of greatest relief or longest strain axis or shortest stress axis. These are molecular rearrangements, sometimes without chemical change, sometimes accompanied by chemical changes. The distinction between the results of shear cleavage and flow cleavage, when shear cleavage is produced at great depths or at high temperatures, is not apparent in the structure itself. The genetic conditions are, nevertheless, different. Shear flow is localized on definite planes or in thin zones. The effect does not pervade the mass. Flow cleavage is a more general result of a pervasive stress in the presence of favorable temperatures and catalyzers.

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[1] *Op cit.*, p. 636.

Flow by Melting.—Flow of rock when melted requires no discussion under the heading of cleavage. It is recognized that rocks melt when sufficiently heated, the degree of heat depending on the confining pressure. It has been stated that melting may occur in connection with shear flow, as a result of the work done on the rock and the rise of temperature; this development may be called *strain melting* and is thought to play a considerable part in the deformation of the body of the earth.

However it is caused, melting completely changes the stress conditions of the locus in which it occurs. The previously existing directed shearing stresses that prevailed in the solid are replaced in the melted rock by hydrostatic stress. If the magma recrystallizes, the structure of the solidified layer or mass is holocrystalline and is adjusted to the uniform stress environment in which it developed. The crystals lack definite orientation and are therefore liable to recrystallize and to assume parallel orientation if brought under differential stresses. Flow by pure shortening and elongation is likely to occur and to involve whatever mass was melted and has solidified. The change is accomplished with the aid of the molecular forces engaged in forming the new crystals and may be regarded as an important source of unbalanced stress in the crust and mass of the earth. Orogenic forces that have become weak may thus be rejuvenated.

SECTION II

CHAPTER VIII

THE PROBLEM OF ROCK DEFORMATION

Rocks have been deformed. Our problem to analyze the conditions of deformation and the forces which caused it. Gravity and molecular forces, differential pressure and differential temperature, minor forces. Static conditions: increase of pressure and temperature with depth; dynamic conditions, necessity for unbalanced forces shown by observed deformations. The forces summarized. Mechanical characteristics of rocks at the surface and in depth considered. The kinds of deformation outlined: fracture, shear, flow, folding, and faulting defined.

THE PROBLEM

It is established by observation in all accessible lands that rocks, everywhere in the continents, have been broken, folded, sheared, squeezed, shortened, elongated, or made over, subsequent to their formation, consolidation, and hardening. All kinds of rocks have been affected in one way or another. The changes they have suffered are extremely variable. They are on a stupendous scale. The masses which have been moved are mountains or even parts of continents. The forces that have been and are now active are extraordinary. The time involved in accomplishing the changes is inconceivable.

While these things are true and superlatives are justified, it is equally true that the scale of effects in mountain growth is great only in relation to human standards. The mass of a mountain is insignificant in relation to the mass of the globe. The force required to fold a series of sediments several miles thick or to crush a thousand cubic miles of rock is inappreciable as compared with the weight of the globe. If we would estimate the phenomena in their true magnitude, we must consider them in relation to the magnitude of the earth.

It is known by observation that rocks bend without breaking, shear smoothly instead of breaking roughly, or undergo chemical changes and crystallize in ways which are different from those in which they break or react chemically at the surface, and it is inferred that the difference is due to the higher temperatures and greater pressures which exist at moderate depths beneath the surface, where the rocks were buried when the bending, shearing, or recrystallizing occurred.

It was long supposed that high temperature was the effective condition which enabled rocks to behave so differently from our common experience of them, and so far as chemical changes are concerned temperature is the more important factor. But the remarkable mechanical changes of form are now known to be made possible by the *confining pressure*, which, being exerted on all sides of a buried rock mass, holds it to a coherent whole, while an additional pressure from some particular direction forces it to change its form.

Finally, it is demonstrable that the mechanical principles which govern the action of breaking, bending, or shearing are independent of the magnitudes of pressures or masses involved, and therefore apply equally to the phenomena on the scale of the earth and to those which we can control.

The problem of structural geology is, therefore, to analyze the conditions under which certain known forces can have produced the observed effects in rocks of determinate character and in accordance with universal principles.

In the discussion which follows we take up in order (*a*) the available forces, (*b*) the conditions under which the forces act upon the rocks at different depths in the earth's crust, (*c*) the mechanics of deformation at different depths as modified by the inherent qualities of different kinds of rocks.

EARTH FORCES

The forces which we may invoke to account for the effects we observe in the structures of rocks and mountains are well known. There is no occasion or opportunity to call up mysterious, hypothetical attractions, such as the " magnetic or polar " forces postulated by Sedgwick nearly a hundred years ago, to account for the effects of temperature and pressure that result in cleavage. All of the phenomena of structures in rocks have been, or undoubtedly may be, explained by the action of forces in forms with which we are well acquainted.

There are two forces which are everywhere existent and always active or ready to act: gravity and molecular forces. The latter include adhesion, cohesion, and chemical affinity. They need no description or definition. They are alike in that they are known to us as attractions. Yet in relation to the structure of the rocks they play different parts, for gravity affects large masses and is effective because of the magnitude of the masses involved, whereas molecular attractions work in the infinitely small. Acting separately or together, they cover the entire scope of magnitudes, from the atom to the globe itself. These are the primary forces.

There are also two secondary agencies: pressure and heat. They are secondary because they are effects of the action of gravity or of molecular attraction, or of both. But in the study of rock structures we recognize them as causes, since we deal with the immediately effective force. The origin of that force is often obscure, for it may be either gravity or molecular force, or both, and it acts under conditions that may evade interpretation.

Pressure acts to move rock masses or to change their form, but only if it is unbalanced. Balanced pressure produces no effect, except one of compression. There must be unequal pressures, and the difference of pressure must be sufficient to do the work, if there is to be any movement or change of form. Heat also must be unbalanced, increasing or diminishing, if it is to effect a change from the state that has existed up to the moment of change. To express the fact of a difference of pressures or of temperatures we use the phrase *differential pressure* or *differential temperature.* And we may say that *the effective force which causes a change in rock structures of any kind is always differential pressure or differential temperature, or both.*

The list of available forces is not complete without the mention of the centrifugal force due to rotation, tidal stress due to external attractions, and magnetic forces. But the effects of these, in so far as they have any geologic effects, are outside of the subject of rock structures. The rate of rotation determines the shape of the spheroid, but not of its constituent parts. Tidal stress may have geologic effect, but only if its transient pull coincides with other conditions, as for instance, if it should release the hair trigger of an elastic earthquake. Magnetic forces probably do not have any effect in the solid earth. Thus we may leave these forces out of consideration as being entirely subordinate or negligible.

STATIC CONDITIONS

While it is true, as stated, that the changes which rocks undergo are the effects of differential pressures or temperatures, it is equally true that the kind of effect which is produced depends upon the static conditions of the immediate environment at the time of the reaction. To take a familiar illustration, water boils at a lower temperature on a mountain top than it does at sea level, because the air pressure, a static condition for the instant, is less in the former than in the latter environment. Similarly, it is necessary to understand the environment of rock masses, that is to say the conditions of temperature and pressure to which they are subjected, at different depths in the earth.

Pressure and temperature both increase from the surface of the earth downward as far as observation penetrates, and there is no doubt but that the increase continues, though we cannot accurately estimate the rate, to the center of the earth. The uncertainties of our knowledge do not, however, materially affect that outer zone in which the structures we have to consider are developed—a thin outer skin, as it were, ten to twenty miles deep. For this external shell we may reasonably accept the rates determined from superficial observations.

Pressure, which is due entirely to the weight of rock resting on a buried mass, increases as we go downward directly with the depth. If the weight of a cubic foot of rock be taken at 175 pounds (specific gravity 2.8), the pressure on each square inch of the base is 1.22 pounds. This is for one foot high and by multiplying we get a pressure of 6,400 pounds per square inch at a depth of one mile. At this rate the weight resting on a rock surface one inch square at a depth of twenty miles is 128,000 pounds. The crushing strength of the strongest rocks at the surface is about one-fifth of this enormous pressure. Hence we may conclude that the rocks at some distance beneath our feet are potentially crushed; that is to say, they would crush if they were not held together by lateral pressures. This is the most fundamental concept of structural mechanics. It was first recognized by the Swiss geologist, Albert Heim,[1] who founded upon it his theories of rock deformation.

We cannot, however, directly calculate the depth at which any particular rock of known strength would crush, because another effect of great pressure is to strengthen rocks. The zone of potential crushing lies deeper, therefore, than we might guess. (See pages 440–449.)

The internal heat of the earth is derived from the compression of the interior under the weight of the outer portion. It is thus an effect of gravity. The temperature is very high in the interior and is lowest at the surface. By observations at accessible depths it has been determined that going from the surface toward the interior there is a normal rise of temperature of 1 degree Fahrenheit for every 60 feet of added depth. According to this the melting temperature of rocks at the surface would not be reached above a depth of 25 miles, and, in view of the fact that melting points are raised by pressures, it is altogether probable that the normal temperature of the earth is below the melting point of rocks at all depths. This view is in harmony with the many facts that demonstrate the solidity of the earth. We are thus prohibited from assuming that rocks are materially weakened by heat, except where local conditions may raise the temperature above the normal for any particular depth.

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[1] Heim, Albert, "Mech. der Gebirgsbildung," 1878.

DYNAMIC CONDITIONS

The normal conditions of pressure and temperature, supposed to exist at increasing depths below the surface of the earth, may be regarded as constant for the epoch corresponding to any displacement of mountain masses. They are static in the sense that any change in their intensities is imperceptible. We are thinking now of general changes, such as those which might be involved in the contraction of the globe. It has been a widely accepted theory that contraction due to cooling is a cause of mountain uplift, but the two processes are incommensurate. In the hundred million years or more of the legible geologic record there has been no recognizable shortening of the earth's diameter, whereas there have been many episodes of mountain growth, any one of which may have been accomplished in one or two million years. The time ratio is as one hundred to one, or is even more disproportionate.

Pressure due to gravitative stress can change only by removal or addition of load, or by a change of density, or both. Any such process is exceedingly slow as compared with deformation. Hence we have described the normal pressures and temperatures as static, in the sense that they are relatively constant.

Nevertheless, the evidences of movement noted in rock structures are so numerous and on so large a scale that it is clear that dynamic conditions exist from time to time; that is to say, conditions of very active movement. These require the development of unbalanced forces and, since rocks are exceedingly rigid and exceedingly strong, these unbalanced forces must be very great.

The origin of these stresses is a matter of hypothesis, which it is not necessary to discuss in order to understand the mechanics of their action. The mechanic does not need to know the chemical reaction which releases the molecular activity of the gasoline to know how the latter drives the automobile. In what follows we consider chiefly the recognized facts of the existence and nature of the unbalanced forces.

Rocks everywhere exhibit the effects of crushing. We see the crevices. The agents of weathering, heat, and moisture discover them when they are still too fine to be seen by the eye. They divide rocks into small blocks. It was found impossible to secure flawless columns 60 feet long for the Cathedral of St. John the Divine in New York, even from the most massive granite mass known in New England. The cliffs of the Yosemite show innumerable shearing planes traversing the great granite mass. Yet granite is the most massive of all rocks. The study of the mechanics of these shearing planes demonstrates that they are effects of very great unbalanced pressure.

Sedimentary strata are known to be laid down originally in flat layers, in a nearly horizontal position. But they are found tilted up and bent double upon themselves. The mechanical analysis of the phenomena shows that they have been subjected to pressure exerted in the direction of the bedding with sufficient force to fold them. As the masses of strata thus folded range in thickness from 10,000 to 30,000 feet, the unbalanced pressure must have been very great. Its initial direction must also have been nearly horizontal.

Many dislocations of the earth's crust are demonstrated by comparison of the masses on one side of the break with their equivalents on the other side, and it has been shown that the segments of the crust thus moved are of the magnitude of mountain chains. Mountains or mountain ranges have thus been thrust 10 or 20 miles from their foundations. The displacements are essentially horizontal in direction and the pressure must have been capable of shearing through the foundations as well as of moving the masses.

It is demonstrable by observation in the large as well as under the microscope that very large bodies of rock, bodies of sub-continental dimensions, have been squeezed thin and correspondingly elongated to several times their original length. The force required thus to affect the intimate internal structure of the mass is even greater than that necessary to move it from its base. It was, moreover, an unbalanced pressure, since the minerals are lengthened in a definite direction, the direction of least resistance.

The groups of facts enumerated are all observed at the surface, but the rocks are known to have been uncovered by erosion and to have risen to the surface from greater or less depths. The structures from which we deduce the existence of dynamic stresses are of a character which could not be produced under surface conditions. They have developed at a considerable depth beneath the surface. Hence, we are justified in concluding that there are conditions which from time to time evolve and bring into play stresses of a temporary character, but of very great power, and that these stresses originate at depths of several miles below the surface of the earth, where they produce dynamic effects.

SUMMARY REGARDING FORCES

From what precedes we may conclude that the agencies which affect any rock mass in the processes of deformation are gravity, heat energy, and molecular attractions, together with such resultants of any of these, singly or in combination, as may develop from local mechanical or physical conditions.

Furthermore, since the activities of deformation are not continuous, but are renewed from time to time, it is evident that the effective forces include a variable, to whose waxing or waning the alternations of movement and quiescence are due. The dead weight does not possess this characteristic, even though it be so great as to develop in the rocks a state of potential crushing. Molecular attractions are in equilibrium, so long as the pressure and temperature conditions are stable. The intensity of heat energy is, however, subject to variation, not in its source presumably, but in its conduction and accumulation. And it is probably through this variable that the potential energies of the molecular and terrestrial gravitations are set loose, in such a manner as to produce deformation of the rock masses.

MECHANICAL CHARACTERISTICS OF ROCKS

Rocks as we know them at the surface are hard, inflexible, brittle, the very symbol of rigidity. Only in very thin layers can we recognize any flexibility. Only some very fine, soft clay rocks exhibit plasticity. To say that a rock will flow is to use words which contradict one another. Nevertheless, the student of mountain structures is forced to recognize that rocks will bend without breaking and will even flow, provided that they be buried deep enough in the earth's crust, for he observes that they indubitably have done so.

The initial suggestion is that the rocks were still soft when they were deformed. We know that wet clay can be forced into the form of a mold or through a pipe, and we reason by analogy that rocks of various kinds may have been put through some similar process while still soft. But the analogy will not stand analysis and the deformed rocks themselves present facts that contradict the assumption. For instance, in a succession of strata we may find pebbles of an older rock in a later conglomerate. It is evident that the older stratum was already hard when the younger was deposited. And yet both strata may have subsequently been folded without breaking. Or an ancient limestone, even a very hard, flinty one, may have been bent during a comparatively recent episode of deformation. There is no question but that the flinty limestone would have been as brittle when folded as it now is, if it had been surrounded by the same slight confining pressure. A critical investigation of the age of rocks at the time they were deformed shows that in general they were so seasoned to resist stress that they must be regarded as having attained their ultimate strength under the environment in which they were buried.

Rocks are strong. That is to say, they can resist unequal pressures up to a large difference. When we put a cube of rock in a testing machine it is surrounded by the balanced pressure of the air. We apply a definite force in one direction, an unbalanced pressure, and we observe that the amount of pressure required to crush the rock is large, as our measures go: 10,000 to 30,000 pounds to the square inch. The rock is strong when surrounded by the universal air pressure, 14.7 pounds to the square inch.

Now let it be assumed that we can increase the air pressure indefinitely and under such conditions that the pressure will be exerted on all external surfaces of the rock mass, but not internally. It may then be called a *confining pressure.* The particles of the rock will be pressed closer together. Will the rock thereby be rendered stronger or weaker? This is a crucial question in relation to the theory of rock deformation and movements of the earth's crust.

Let the confining pressure be raised to 30,000 pounds, equal to the crushing strength of the strongest rocks under the pressure of the atmosphere alone. Will the rock be crushed? No. Confining pressure which acts equally on all external faces cannot crush a solid, in the sense of breaking it down. It can compress it, but to the extent that it does so it forces the particles into closer relations and reduces their freedom of movement. A rock is thereby made stronger.

KINDS OF DEFORMATION

The first section of this book is devoted to a description of rock structures. Omitting original structures of sedimentary and igneous rocks there remain folds and flexures, joints, faults, cleavage, and flow structure, which are produced by the process of deformation. Changes of form in rocks may be achieved by fracture, shear, or flow. These are the primary kinds of deformation. Special combinations of them are found in folding and faulting. This chapter analyzes these processes according to the principles of mechanics outlined in the preceding chapter.

Definitions.—A fracture is an open break. The term carries with it the idea of a separation of the parts into which a mass or particle has been broken. Size is not an item in the definition. Fractures may be miles in length, thousands of feet deep, and proportionately wide; or they may be microscopic in all dimensions. At the time of the breaking, the fracture opened. Whether it be immediately or subsequently closed, the closing none the less followed opening.

A fracture is a rough break. The direction and the details of the surface of fracture are determined by the internal strength and resistances of the material fractured. In these respects fracture is distinguished from shear, but as will appear shear may develop from fracture or may disperse into fractures.

Shear is a smooth cut. It is that kind of a parting of a mass which is produced when the blades of scissors pass one another in opposite directions. If they are close together we get a clean cut. If they are not very close, the material between them is turned to one side, is rotated and laid more or less nearly parallel with the shear. Shear is therefore associated with rotation, but in rocks the film in which rotation occurs is often so thin that the parting appears as a smooth plane.

Shear is produced by the action of two opposed forces which are not directly in line with one another. The two forces constitute a force couple. Their combination is a shearing or rotational stress. Stress and shear bear a definite mathematical relation to the direction of the pressure which causes deformation. Any possible planes of weakness in the material subjected to shear may affect the direction of the shear planes so that the mathematical relation is modified. The shear may thus be diverted into planes in which it would otherwise not take place, or it may be rendered irregular and become a fracture. There is, however, a sharp distinction to be made between deformation by fracture, which is directed by the weaknesses of the rock, and deformation by shear, which is controlled by the intensity and direction of external pressures. This distinction cannot be appreciated in all its significance without a discussion of the relation of fracture and shear to the confining pressures, which is given in the analysis of the conditions that govern each mode of change of form.

Flow is a change of form without apparent rupture. It will be shown that the appearance is probably nothing but a question of proportion and that flow is sub-microscopic or molecular shear. Under the microscope we detect shearing which escapes our unaided eye but which obeys the laws that distinguish shear. Those laws are independent of size, and it is reasonable to infer, though not now possible to prove, that they govern the form of displacement which we know as flow. Flow and shear appear to be intimately related mechanical effects if not the same. Flow, however, may occur in consequence of the development of new minerals, at least in those cases where it is most perfectly developed, and the term will be used with that implication, even though it also carries the idea of microscopic or sub-microscopic shear. Flow, like shear, is controlled by external forces rather than by internal resistances.

A fold is a bend. Only bedded rocks and laminated rocks can bend in such a way that the form of the bend can be recognized; in fact it is only through their laminated character that bends can be produced, hence the term fold is limited to the forms which they take. The degree of folding does not enter into the definition. A gentle flexure is therefore a fold, as is also a closely compressed crease. It is, nevertheless, good usage to call a flexure a flexure and not a fold. The definition cannot be limited by the mode of action of the forces to which a fold may be due. They may act in a horizontal or vertical or inclined direction, parallel to or across the strata, but if the strata are bent the structure is a fold in any case. This definition must be carried even farther, and the term fold may be applied to the form assumed by strata when laid down, as it is often difficult to distinguish between folds of deposition and gentle flexures caused by subsequent deformation.

In this respect the term folding is broader than that of warping, which is a deflection due to vertical forces, and fold is more comprehensive than upwarp or downwarp.

Folding requires both the extension and compression of rocks and can take place, therefore, only under those conditions where these reactions are possible. Extension and compression require, however, either fracture or shear or flow of the rocks involved, and folding can therefore occur only where one or two or all three of these phases of deformation may take place.

A fault is a shear or a fracture on which there has been an observable displacement of the two parts of the mass parallel to the plane of the break. Faulting is distinguished from fracture, because in the former the observable displacement is parallel to the plane of parting, while in the latter the movement, whether inferred or observable, is at right angles to this plane. It is distinguished from shear by the fact that in case of shear, though mechanically there must have been displacement parallel to the plane of parting, the shear is recognized as a fault only when the displacement becomes observable.

CHAPTER IX

MECHANICAL PRINCIPLES

Definition of terms: stress, strain, equilibrium, shearing stress, etc. Stress and strain axes in nonrotational and rotational stress. Relation of deformation to strain axes constant. Interpretation of stress from strain. The effects of torsion.

The deformation of rock masses by fracture, shear, or flow, or by folding and faulting, is a mechanical process that is always subject to the laws of mechanics. The application of the controlling principles to any case enables us to analyze the deformation, to interpret the facts of structure, and to infer the nature of the stresses.

Before proceeding to the analysis of the various types of rock deformation it is necessary to define certain terms and to outline the simple mechanical principles to be employed. This chapter considers the different ways in which forces may act on a body to deform it, and shows that deformation can be reduced to a simple formula in which the stresses are represented. In the following chapter the relation of deformation to the axes of strain will be discussed.

DEFINITIONS

Stress is force. When sufficient stress is exerted on a body deformation ensues.

Strain is the deformation caused by a stress. It should be carefully distinguished from the stress, as this distinction is of great importance in interpreting the results of deformation.

Resultant stress is the stress which acting alone would have the same effect on a body that all the stresses actually acting on it have. Technically it is the vector sum of all the stresses acting on a body.

Stress couple or *couple* designates two equal, but opposed, parallel forces that are not in a line. See rotational or shearing stress.

Equilibrium is that state in which the resultant of all forces acting on a body is zero.

Unbalanced stress is a stress which acts on a body and is not balanced by another equal and opposite stress. When an unbalanced stress acts on a body that body is not in equilibrium, and movement (deformation) ensues.

Nonrotational stress is that condition in which every stress acting on a body is balanced by an equal directly opposed resistance.

Rotational stress, *shearing stress*, and *couple* are synonymous terms for two forces of equal intensity acting on a body in opposite directions, but not in the same line. Such a combination of forces tends either to rotate the body or to shear it along lines parallel to the two forces, hence the names rotational and shearing stress.

Torsion is the combination of two rotational stresses (couples) acting in parallel planes about a common axis, but in opposite directions. Torsion is a twist, and produces the most complicated type of deformation possible in a simple system.

Stress Axes.—If a system of nonrotational forces acts on a body, all the forces can be resolved into components in three directions at right angles to each other. These three directions are called the stress axes, or axes of stress, and should be so chosen that one is parallel to the resultant, or to the components of the forces which give the greatest stress exerted on the body in any one direction. The components in the other two directions will then show two sets of balanced forces, which may, however, be unequal. Let us assume that all the forces are compressional, and that the body is in equilibrium. One of the axes will be parallel to the greatest compressive force. Another will be parallel to the least compressive force, and its direction is known as the *direction of least resistance.* The direction of least resistance is of great importance in the orientation of rock structures.

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Strain

It should be noted that in any system of stresses acting on a body in equilibrium, the balancing forces may be, and in the rocks

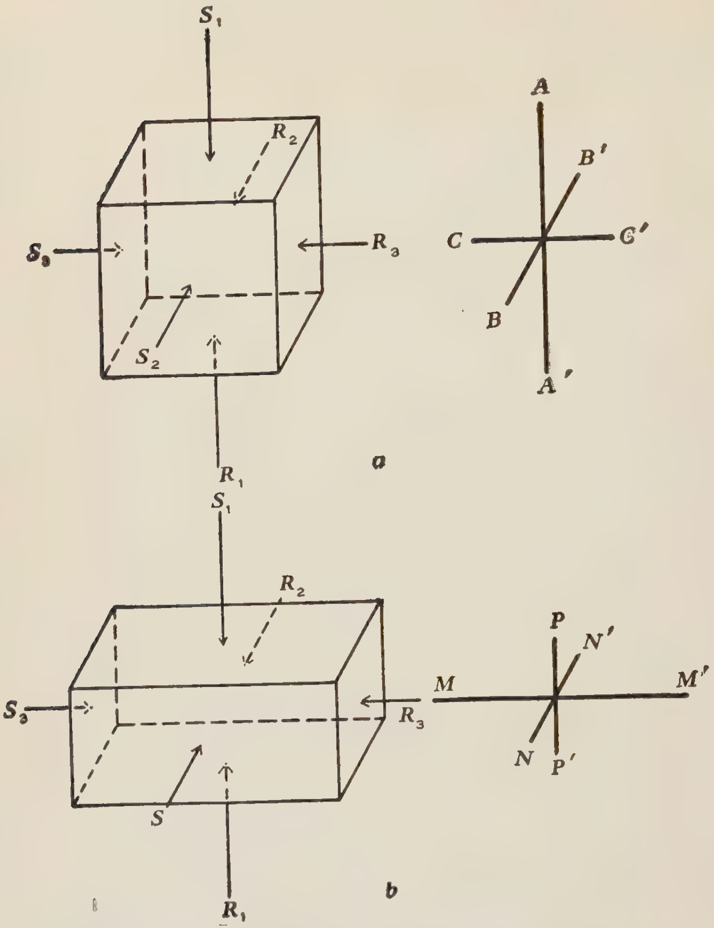

FIG. 92.—Nonrotational stress, showing stress and strain axes.

S_1, greatest compressive stress
S_2, intermediate compressive stress.
S_3, least compressive stress.
a, Stress axes:
AA', axis of greatest stress.
BB', axis of intermediate stress.
CC', axis of least stress, or direction of least resistance.
b, Strain axes:
MM', axis of elongation.
NN', intermediate strain axis.
PP', axis of shortening.

If the stresses include tension the values on one or more of the stress axes may be negative.

beneath the surface of the earth generally are, the internal resistances of the rock. When the external forces become greater than the strength of the rock they destroy the balance and cause deformation of the rock.

Strain Axes.—Let us assume that the greatest stress in the above example increases until deformation ensues. The body changes its shape, becoming shorter in the direction of compression and being elongated in the direction of least resistance. In the third direction, at right angles to these two, the dimension may remain unchanged or may be either lengthened or shortened, depending on the relative magnitude of the stresses acting in this direction; but the effect will be intermediate between the shortening and lengthening in the other two directions. These three directions may be called the *axes of strain*, for measurements in them are sufficient to describe the change of form of the body. The direction in which elongation has occurred may be called the longest strain axis, or the *axis of greatest elongation*. The direction in which shortening has occurred is the shortest strain axis, or the *axis of greatest shortening*. The third axis is the *intermediate strain axis*. It is readily seen that in the case of a nonrotational stress as assumed above, the stress axes and the strain axes are parallel, but if compressive stresses are taken as positive, the greatest stress axis is parallel to the shortest strain axis, and the least stress axis is parallel to the longest strain axis.

It should be noted that the strain axes are measures of the shape of the deformed body, and not of the amount of deformation. Thus the greatest dimensional *change* may be either in shortening or in lengthening, but this may not influence the position of the strain axes.

Leith has evolved a simple concept whereby the strain axes may be better understood. He assumes a hypothetical sphere in the mass before deformation. After deformation this sphere becomes an ellipsoid. He has called this figure the *strain ellipsoid*.[1] Its axes are the axes of strain.

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[1] Leith, C. K., "Structural Geology," revised. (Henry Holt and Co.) 1923, p. 21.

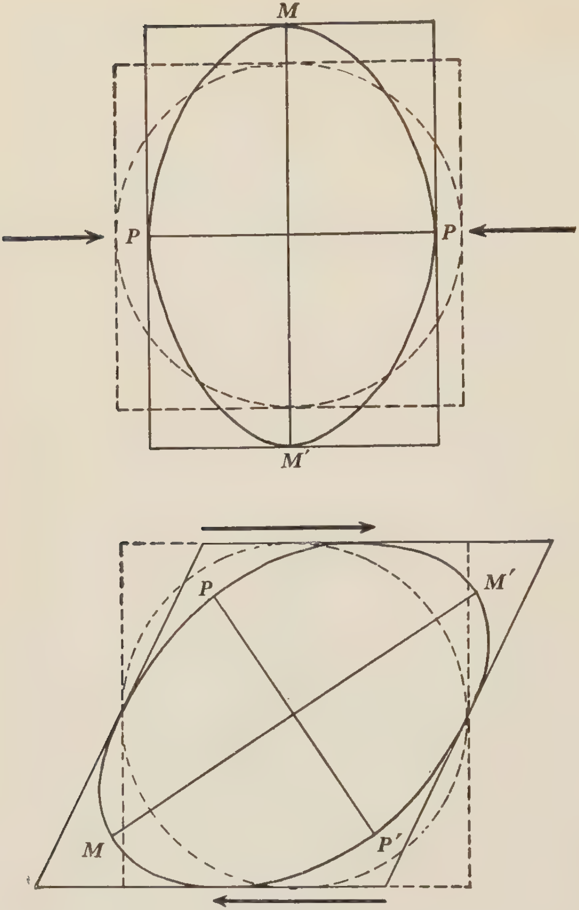

Fig. 93.—The strain ellipse.

a. Nonrotational stress.
b, Rotational stress.
MM', axis of elongation.
PP', axis of shortening.

Deformational effects are usually considered only in two dimensions. This is due to the fact that usually the axes of greatest elongation and of greatest shortening can easily be recognized. A cross-section of the strain ellipsoid in the plane which includes these two axes shows an ellipse which represents the original circular cross-section of the sphere. The axes of the ellipse are the axis of elongation and the axis of shortening of the mass as a whole. This figure is referred to as the *strain ellipse*, and is illustrated in Fig. 93. The usefulness of this strain ellipse and the strain ellipsoid has been recognized, and they have found their place in American literature on the mechanics of rock deformation.

Deformation by Rotational Stress.—If one or more couples act on a mass there is always a single resultant couple which has the same effect as all of the actual couples combined, unless the mass is in equilibrium, when all couples will balance one another. Assuming the case of a resultant couple of sufficient strength to overcome the internal resistance of the mass and hence to cause deformation, the effect of this deformation will be to move the particles of the mass past each other in directions parallel to the forces of the couple (Fig. 94). This causes a lengthening of the mass in a direction diagonal to the forces of the couple, but in their plane. It also causes a shortening at right angles to the direction of lengthening, but also in the plane of the couple. The third dimension of the mass, at right angles to these two and therefore at right angles to the plane of the couple, is not affected unless forces other than the couple act on the mass. We have, therefore, the same effect produced by a couple that we found as a result of nonrotational forces, namely lengthening of the mass in one direction, shortening in another, and a change, if any, intermediate between the two in the third direction. Again we can call these three directions of change the axes of strain. The figure produced by the shearing stress is the same as that produced by nonrotational stress, and it can be shown that *the relation of the different types of deformation to the strain axes is always the same.* The necessity for the use of the strain axes arises from this very similarity of effect produced by two different systems. The recognition of the position of the

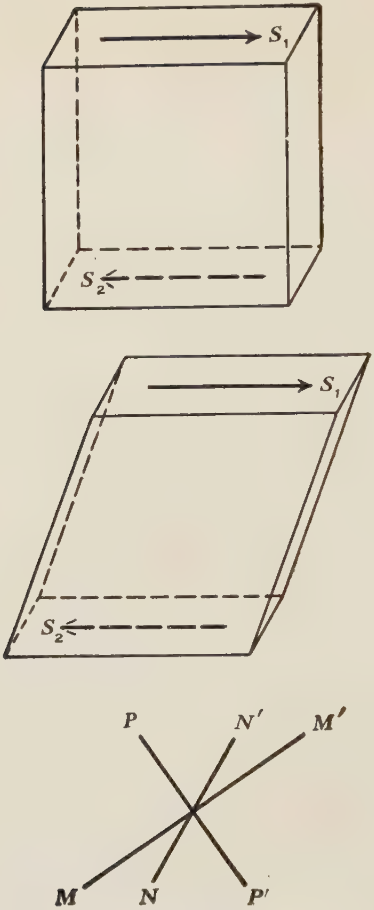

Fig. 94.—Rotational stress, showing position of strain axes.

S_1, S_2, Forces of the couple.
MM', axis of elongation.
NN', intermediate strain axis.
PP', axis of shortening.

strain axes is usually simple, when considering any individual case of deformation; the interpretation of the force system which produced it is much more difficult.

The most essential difference between the effects of nonrotational and rotational stress systems is that in the former the strain axes retain their initial position, and remain parallel to the stress axes, whereas in the latter the strain axes are rotated during deformation. The initial position of the axis of elongation is at 45 degrees to the direction of the forces of the couple, but as deformation proceeds it tends to become more and more nearly parallel with this direction.

Interpretation of Stress from Strain.—From the foregoing paragraphs it is evident that in any individual case of strain there may be more than one interpretation of the possible stresses that have caused it. In nature, how is one to decide whether the stress has been rotational or simply compressive? The answer seldom lies in the evidence found at any given locality, but rather in the distribution of deformation over a large area. In many areas the effects of both types of forces are found. For instance, if a part of the earth's crust has moved, compression may be expected directly in front of it, whereas shearing stresses in a horizontal plane should have acted on either side of it, where it moved past adjacent masses. In folding it will be shown that in the different parts of a fold compression, tension and shearing stress are all present. *Any local stress will produce strain axes oriented parallel to other local strain axes, and these will all be parallel to the strain axes which would result from the major stress causing the folding.* When fracture, shear, and flow are found in a rock mass each type may be interpreted individually to give a certain set of strain axes, but *all sets thus derived are similarly oriented.* This is the most important principle in the interpretation of rock structures, and finds its application in many practical problems, such as the determination of the axial position of folds from the flow cleavage; the determination of the position of a bed, whether normal or overturned, from drag folds, shear joints, or tension cracks; the location of cross folding on echeloned normal faults; the interpretation of fault

Imp

movements and the nature of faults, whether normal or reverse, and many similar problems, both local and regional. Some of these problems are discussed in the following chapters on types of deformation. Others are suggested in the descriptions of structures in the first section of the book, and regional relations of different types of deformation are considered in the descriptions of the structure and the outline of the structural history of type regions.

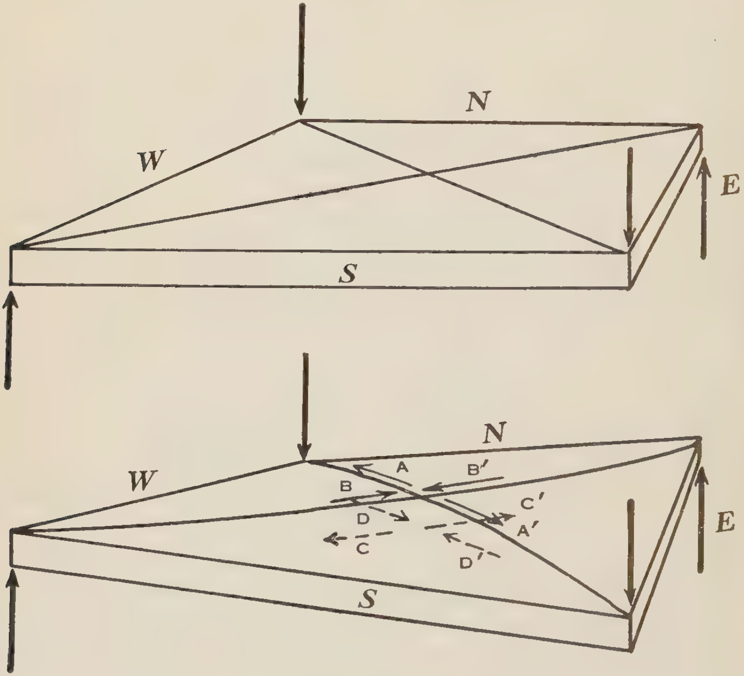

FIG. 95.—Torsion.

AA′, direction of tension (axis of elongation) in the upper surface.
BB′, direction of compression (axis of shortening) in the upper surface.
CC′, direction of tension (axis of elongation) in the lower surface.
DD′, direction of compression (axis of shortening) in the lower surface.

Torsion.—Torsion is the one type of stress system which, contrary to the above statement, produces strain axes with different orientations in different parts of a mass. This is obviously due to the fact that two sets of forces act on the mass, in opposed directions, and the strain axes produced by them should therefore have opposite orientations. Consider a stratum of rock deformed in such a way that the northwest and southeast corners of a rectangular area are depressed, while the southwest and northeast corners are raised, the central point remaining stationary. Such a movement would be the result of torsion due to two couples in vertical planes acting in opposite directions along either the north and south or the east and west edges of the area. The resulting shape would be that of a saddle. The deformational effect at the center would be that of two folds at right angles to each other, one concave upward with a northwest-southeast axis, the other convex upward with a northeast-southwest axis. On the upper surface of the stratum this would produce compression across the axis of the former, or in a northeast-southwest direction, and tension at right angles to it across the axis of the latter. The strain axis of elongation resulting from these stresses would be parallel to the tension, the axis of shortening parallel to the compression. On the under side of the bed, however, the condition would be reversed, and the strain axes would be oriented at 90 degrees to those on the upper side.

The above example describes the commonest case of torsion found in general geologic practice, that of the twisting of horizontal strata due to gentle differential uplifts or depressions. Many of the structures in nearly horizontal sedimentary rocks may be due to systems of stresses of this kind.

CHAPTER X

PRIMARY TYPES OF DEFORMATION

Separation of the parts the requisite of fracture; fracture develops normal to axis of elongation, but is controlled largely by internal lines of weakness. Shear a clean cut, controlled by external forces; shear in compression, the angle between the shear planes and the factors which determine it, shear in rotational stress; shear by combined stresses, its significance in folding; spacing of shear planes, curved shear planes due to deflection of stress; the effects of torsion and shear compared. Flow analyzed and three types distinguished according to varying relations of the strain axes.

ANALYSIS OF FRACTURE

Fracture, as the word is used in this work, means a rough break. It is distinguished from shear, which is a smooth break. The first is due to tension, the second to compression or rotational stress. When a substance fractures, the adhesion or cohesion existing between the particles is broken and they are so separated that they no longer adhere. The direction of the fracture is primarily controlled by the tension or blow, but the internal resistances or weaknesses are influential, and in determining the details of the broken surface they are dominant.

A conglomerate breaks around the pebbles, a sandstone around the grains, a shale along a parting in the clay, a limestone or glass with a conchoidal fracture determined by the elastic vibration of the material.

Ordinarily, we are not concerned with the external environment of the material. The surrounding air pressure is negligible. But when substances are under greater pressures they can part only in case they are strong enough to bridge any opening which the

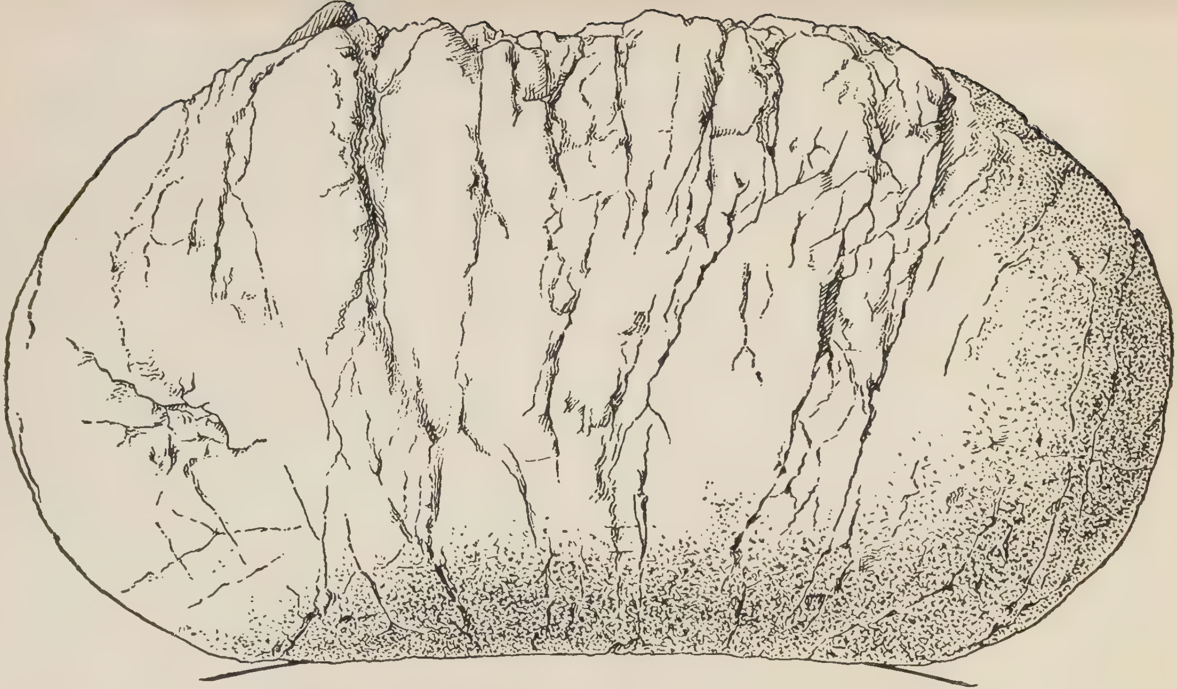

FIG. 96.—Drawing of a granite pebble, fractured by bending over another pebble.

Specimen from Eocene conglomerate involved in the San Andreas upthrust fault, near Loma Prieta, Santa Cruz mountains, California. The specimen shows the effect of bending and fracture by tension under moderate confining pressure. The pebble on the upper left hand was pressed into it. The lower surface of the bent pebble was flattened over the one on which it rested.

parting may produce. Hence, the greater the general pressures, the stronger must be the material in order that it may fracture.

Bridging implies an opening and an open space is characteristic of fracture. The space may be round or flat, large or small; it may be an open fissure, such as is filled by a vein, or a crack in a sand grain. In all cases the idea of fracture implies an open space, separating the walls beyond the radius of attraction of adhesive or cohesive forces and remaining open an appreciable time.

The forces involved in fracture are three: an unbalanced force which causes the break, the inherent strength of the material which resists it, and the balanced confining forces which aid the resistance. If fracture occurs the first must be enough greater than the other two to separate the pieces.

If we consider what forces are active at the surface or near it to cause fracture, we find that they are due to changes of temperature, the mechanical or chemical activity of water, or localized effects of gravity. Temperature changes of rocks disrupt them because the different mineral constituents expand and contract unequally. Water, freezing in crevices, breaks the blocks apart. Moisture, entering into combination and forming hydrated minerals, causes the altering material to expand and exert great pressure. Gravity may be localized by a weakening of the resistance opposed to it, as when water percolating on a seam lubricates the surface and reduces friction, or when in the progress of earth movements a mass becomes unbalanced and throws its weight on one side. None of these effects can be regarded as a major incident of rock deformation. They occur only where the absolute strength of the rock is weakest and where the confining pressures are least.

Beneath the surface fracture may be occasioned by the vibrations of an earthquake shock or of a volcanic eruption, within the areas of such activities. The more general cause, however, is the bending or displacement of masses where the unbalanced stresses are sufficient to produce movement, but the confining pressures are not adequate to force the rock to shear. Fracture is therefore a common associate of folding and faulting.

Heim[1] investigated the relations of fractures to folds and described them minutely as they occur in the great overfolds of the Alps. His description has general application and may be summarized as follows: the great arches of the major folds seem to have been developed without breaks, but on examination it is found that they are traversed by many veins of quartz or calcite. Since the sides of any vein would fit together, if the vein matter were removed, it follows that the veins are equivalent to older, open fissures. He observed that the number of veins increased with the sharpness of the folding in the same stratum and locality. With reference to the occurrence of fractures in different parts of a fold, it is observed that within an arch, where the strata are under lateral compression, there is extension in the direction of the radii. Hard, brittle rocks, which because of their hardness were in the zone of fracture, may there be torn apart in the direction of the radii, where softer rocks suffer plastic deformation. Such structures are characteristically irregular. On the outside of an arch, on the contrary, the stretching of the strata in bending produces a tension-stress which may cause a strain in the direction of the tangent, with the result that fissures, proportionate in number and size to the acuteness of the bend, develop at right angles to the tangent and generally parallel to the axis of the fold. They will be parallel to the strike of the beds only if the axis of the fold is horizontal.

By detailed measurements Heim determined that the total spaces represented by the fissures corresponded fairly well with the amount of stretching demanded of any individual bed, but if greater thicknesses were taken into account there was a marked deficiency. He thus demonstrated that the beds had not bent as one bed, but each one for itself, and the excess of stretch required by the whole thickness had been adjusted by slipping of the strata on one another. This is one of the principles of adjustment in folding.

In case the bending of strata takes such a form that there is a torsional strain, conjugate joints may be developed, as is explained under jointing, and these may become open fissures in one or both directions. The mass of a stratum may thus be separated into detached blocks.

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[1] Heim, Albert, "Mech. der Gebirgsbildung," vol. 2, pp. 12–31, 1878.

In general it is to be said of deformation in the zone of fracture that it is governed by the lines or surfaces of weakness in the rocks, but in homogeneous material fracture planes will assume a definite relation to the axes of strain. The direction of greatest elongation of the mass is naturally the direction of tension. The mass will tend to part in the way which offers the least resistance, that is, if adhesion is uniform in all directions within the rock, on a plane at right angles to the direction of greatest elongation. Stated more briefly, fracture will normally develop perpendicular to the axis of elongation. All planes of weakness in the rock, however, will tend to divert it from this ideal position, and fractures can seldom be used as reliable criteria by which to interpret the position of the strain axes. Joints formed by compression may in a later stage of deformation open as fractures. Bedding planes will part, even when they make a comparatively small angle with the direction of tension. Fractures are often observed which are offset at each bedding plane, the general line of fracture corresponding approximately with the

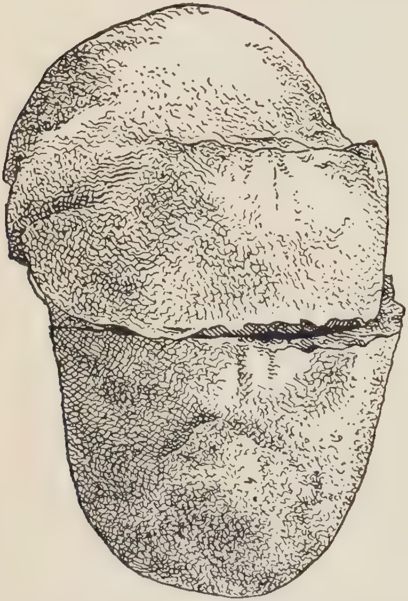

Fig. 97.—Drawing of a pebble which exhibits fractures that approximate the regularity of shearing, the matrix around the pebble having been in the zone of shear, whereas the pebble was in the zone of fracture. Cretaceous conglomerate, Alum Rock Creek, Mt. Hamilton Range, California.

theoretical position, but the fracture following a zigzag path because of the ease of movement on bedding planes.

ANALYSIS OF SHEAR

A shear in rock has been described as a clean cut. The illustrations drawn from specimens and reproduced in Figs. 35 and 88 serve to show how very smooth and flat the parting of a rock may be on a plane of shear.

In mechanics a shear is defined as a parting or tendency to part under the action of two parallel but opposed forces, which are not in line with one another. The action of the two blades of a pair of scissors is to produce a shear in the material cut. An iron plate is sheared when it is punched, the edges of the punch and die passing one another as the piece is sheared out. In these cases the shearing forces originate outside of the body that is sheared. A similar effect is produced when the overturned limb of a fold is

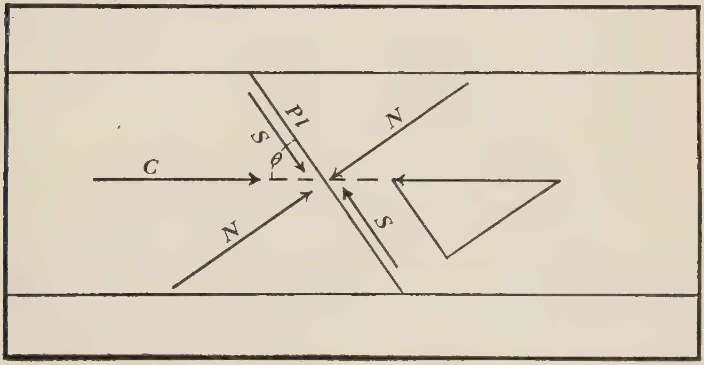

Fig. 98.—The relation of the shearing components S and the perpendicular or normal components N of a compressive stress C, to any plane Pl making an angle θ with the direction of compression which is of course parallel to C. (After Lovering.[1])

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[1] Lovering, T. S., The Fracturing of Incompetent Beds, Jour. of Geol., vol. XXXVI, p. 711, 1928.

crushed and drawn out between the upper and lower limbs, which move in opposite directions. It is sheared.

Shear Due to Compression.—A column or cube of rock may fail by shearing if a sufficient load be placed upon it, but in that case there are no external jaws or blades between which it is cut. The external force is one of simple compression. The column or cube transmits the pressure, which is resolved, on any plane in the cube, into parallel and normal components. The component parallel to the plane tends to produce shear in that plane and may be called the shearing component. Its intensity varies with the angle between the plane and the direction of compression. It can be shown mathematically that it reaches a maximum when this angle is 45 degrees. If there were no friction, and if the body were non-elastic, shear planes would develop at this angle to the compression. Friction produced by the normal component aided by the elasticity of the material modifies this angle, but it is constant for a given substance under given conditions of confining pressure and temperature.

In the case of deformation by a single external nonrotational stress there may be any number of such planes, oriented at equal angles to the direction of stress, in a circle around the point of its application. The theoretical surface of shear would thus be a cone. Where resistances are equal the tendency is to form three sets of shear planes in place of the cone, as this is the least number which gives relief in all directions normal to the pressure. This case is rare in nature because the resistances are never ideally equal. Where the sheared mass is subjected to confining pressures, and where these vary so that the three stress axes are unequal, two intersecting sets of parallel planes take the place of the cone. This is easily understood by reference to Fig. 99.

The shearing stresses set up on the surface of the cone of maximum shear are opposed by the components of the confining stresses parallel to this surface. By the law of least work, failure takes place in the direction of least resistance. The maximum shearing stress on the surface of the cone is that opposed by the least resistance; hence it lies in the plane of the greatest and least stress axes.

The planes of shear lie at right angles to this plane. Relief may be found in either direction along the axis of least stress; hence two sets

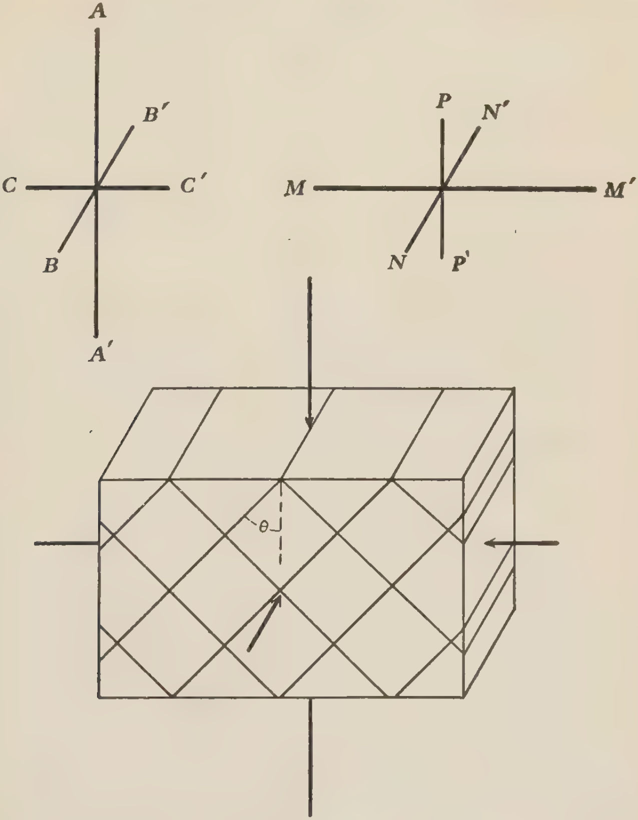

Fig. 99.—Shear planes developed by compression:

AA', BB', CC': stress axes.
MM', NN', PP': strain axes.
θ: angle of shear.

of planes develop, making equal angles on either side of the direction of maximum stress. This angle (θ in Fig. 99) between the shear planes and the direction of pressure is the *angle of shear*, and is constant under a given set of conditions.

There has been much discussion of the mechanical conditions which determine the angle of shear. Lovering[1] has summarized the differences of opinion regarding it (whether more or less than 45 degrees) and also the factors that determine it. The latter include in any particular case the direction of stress and the nature of the strain. One group of investigators,[2] however, has considered only stress; another[3] has taken account only of strain. Yet either may be right, if the conditions happen to fit the conclusion reached. Those who consider stress alone conclude that the angle by which the shearing plane diverges from the direction of maximum pressure must be less than 45 degrees and that the acute angle of the shearing rhomb formed by the two sets of shear planes will face the pressure. The other school reasons that the angle will be greater than 45 degrees and that the obtuse angle of the rhomb will face the pressure. Both groups omit to consider other determinant factors, as appears from Lovering's explanation, which follows:

> A complete theory must consider the effect of both stress and strain; and in considering the failure of an ideal homogeneous isotropic body, the following variables must be taken into account; (1) friction; (2) the molecular binding force; (3) strain, or the elastic deformation suffered before rupture; (4) the shearing or parallel components of stress; and (5) the normal or perpendicular components of stress. (See Fig. 98.)

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[1] LOVERING, T. S., The Fracturing of Incompetent Beds. *Journal of Geology*, vol. XXXVI, pp. 709–717, 1928.

[2] WITHY, M. O. and JAMES ASTON, "Johnson's Materials of Construction" (John Wiley and Sons, 1925), p. 15.

MERRIMAN, MANSFIELD, "The Mechanics of Material" (John Wiley and Sons, 1924), pp. 378–379.

MOHR, O., "Welche umstande bedingen die Elastizitatsgrenze und die Bruch eines Material," Zeitschr. D. Ver. Deutsche Ingen., vol. XLIV (1900), pp. 1524–70.

BUCHER, W. H., The Mechanical Interpretation of Joints, *Jour. of Geology*, vol. XXIX, (pp. 1–28, 1921).

[3] BECKER, G. F., Finite Homogeneous Strain, Flow and Rupture of Rocks, *Bull.* Geol. Soc. Amer., vol. IV, pp. 17–90, 1892.

(1) The larger the coefficient of friction, the smaller will be the angle of fracture facing the axis of compression, since friction varies with the normal component. (2) An examination of Merriman's formulas indicates that θ will vary from 0° to 45° as the molecular binding force varies from 0 to ∞. In other words, the larger the molecular binding force, the greater will be the tendency of the material to fracture with an angle of 45° to the compressive force. (3) As Becker has shown, the greater the strain or elastic deformation preceding rupture, the larger will be the angle of fracture facing the axis of compression. (4) The shearing components of stress actually cause the fracturing (shearing); and since they are decreasingly effective on planes of more and less than 45° to compression, they will tend to localize fracturing on planes whose angle to compression is about 45°.

(5) The normal or perpendicular component of stress increases both molecular binding force and friction, and thus the difficulty of causing movement on any plane increases as this component becomes larger. It is least along planes making very small angles with the direction of compression, and hence it tends to decrease the angle of fracture.

In nearly all substances the influence of friction is much greater than that of strain; and, as a result, most substances break with angles of less than 45° to the axis of compression. In other words, the angle 2θ in Fig. 98 is usually less than 90°. Even if we imagine a rock in which friction is non-existent, there are few that would undergo sufficient elastic compression before failure to produce angles of fracture much greater than 45°. However, some highly elastic materials such as wood, soap, mild steels, and a few other substances fracture with obtuse angles facing compression.

Experiments conducted under laboratory conditions, on rocks, metals and other substances of low compressibility (elasticity) and considerable strength, tend to confirm Lovering's conclusion that the angle of shear is less than 45 degrees. Observations in nature have also been made which can be so interpreted.[1] Nevertheless, other observations indicate that the opposite relation may also exist.[2] In the California Coast Ranges the direction of stress shown by all other structural relations bisects the obtuse angle formed by sets of joints in homogeneous granite. Two sets of joints are recognized, an earlier and a later. Both are intruded by dikes, the earlier by those of aplite, the later by basalt. Both were sheared under great confining pressures. It is probable that the relations of stress in deeply buried rocks differ from those that we may observe in the laboratory and that the angle of shear may be greater where the *relative strength* of the rock is less, though the *absolute strength* is greater. The problem involves all five of the variables named by Lovering and we do not know how they vary nor how their relative values may change as confining pressure increases with depth. Theoretical conclusions had best wait on more extended and carefully checked observations.

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[1] Bucher, W. H., *op. cit.*

[2] Willis, Bailey, La Force Seismique en Californie. Livre Jubilaire de la Société Géologique de Belgique, p. 33, 1927.

The actual state of knowledge may be expressed in terms of the positions of the strain axes, as follows: *The angles of the rhomb formed by two intersecting sets of parallel shear planes are bisected by the axis of elongation and the axis of shortening, but either may bisect the obtuse angle of the rhomb. The intermediate strain axis lies parallel to the planes of shear.*

Shear Planes Due to a Shearing Stress.—So far only the effect of nonrotational compressive stress has been considered. The name shearing stress implies that such a combination of forces can produce shear planes. It can be shown that a single shearing stress tends to produce two sets of shear planes, similarly oriented with respect to the strain axes as those produced by compression. Experimental data and theoretical considerations indicate, however, *that in pure rotational stress the obtuse angle between the two sets of shear planes faces the axis of shortening.*

Figure 100 shows the theoretical development of the two sets of shear planes. The most natural relief of strain is on planes parallel to the direction of the forces of the couple, but at right angles to the plane of rotation (shear planes AA'). The same effect of deformation can be produced by the division of the mass on planes at right angles to these (shear planes BB') and the rotation of the blocks between them, permitting slipping on them. These two sets of planes are planes of no distortion. At the beginning of deformation they lie at angles of 45 degrees to the greatest and least strain axes. They are the theoretical planes of maximum shear.

Let us consider the factors which may modify their position in the rock. The principal factor which tends to change the position of such planes in the case of compression is the internal friction of the rock, produced by the component of stress normal to the plane of shear. In the case of simple shear there is no component of stress normal to the plane which parallels the stresses of the shearing couple. On the plane that lies at right angles to them each stress exerts its full force, but its normal component will vary equally if the angle that faces the least strain axis be increased or decreased. If the substance is elastic, deformation before failure by shearing will not change the position of the first shear plane, but will incline the other in the direction of rotation, making the angle which faces the least strain axis obtuse. For these reasons we conclude that *in pure rotational stress* this is the case.

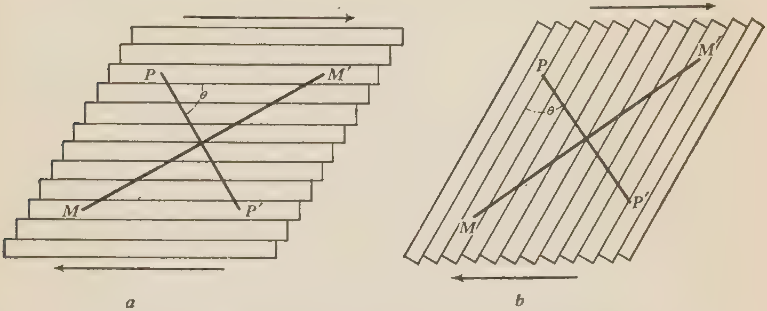

FIG. 100.—Shear planes developed by a shearing stress:

a, planes developed parallel to the forces of the shearing couple.

b, planes developed at right angles to the forces of the shearing couple, and rotated by them.

MM', *PP'*: strain axes.

Geologically the case just considered may be rare. It may be found locally in an area in which there is differential movement in a horizontal plane in the basement rocks. Such a case can readily be imagined on the margin of a mass that is thrust into the mass in front of it, as on the margin of an arcuate mountain system. In the vertical plane, however, it is doubtful if simple shear ever exists without accompanying compression. It is difficult to reproduce it experimentally. Leith and Mead have conducted various experiments on shearing, two of which are figured in Leith's Structural Geology.[1] In one of these they put a layer of paraffin on a rubber sheet stretched between two clamps, and moved one edge parallel to the edges of the sheet. This produced a simple shearing stress, as there was no shortening of the mass at right angles to the direction of the shearing forces. In the other experiment a cube of Bedford limestone was deformed by the diagonal application of stress to a frame which fitted closely around the rock, but which was arranged so that the angles at the corners could vary. This did not produce pure rotational stress, as there was shortening at right angles to the shearing stress. The effect was actually one of two shearing stresses at right angles, and their result was the same as that of simple compression acting along a diagonal of the cube. It is noteworthy that in this case the two sets of shear planes developed form a very *acute* angle which faces the least strain axis, or the direction of compression, while in the case of the paraffin mounted on rubber, where the stress is simple shear, the *obtuse* angle between the two sets of shear planes faces the least strain axis.

Shear Due to Combinations of Stress.—The case of combined compression and shearing stress is common in nature, and demands special consideration. The commonest example of it is found in the beds on the limb of a fold, where compression is due to the major external stress that causes the folding, and shearing is produced by the movement of the beds on one another parallel to the bedding planes. This case is shown in Fig. 101. The planes which are commonly developed lie diagonal to the bedding planes, at angles varying from almost 90 degrees to extremely acute angles. In the weaker beds, in which most of the deformation has been accomplished, they are rarely more than 60 degrees. They are best explained as the result of the combined effects of the compressive and rotational stresses. The compression tends to produce elongation in the direction M_1, the shear in the direction M_2. The compression will find relief on shear planes A and B, the shear on C and D. The actual direction of elongation is intermediate between M_1 and M_2, or at M_3, the exact position being determined by the relative importance of the compression and the shear. The theoretical positions of the planes of shear are therefore at E and F. Plane F is nearly parallel to the bedding, hence it is likely that the planes of weakness between beds will influence its development, and movement will occur on them. Plane E is inclined to the bedding as described above. The greater the influence of the compression, the smaller the angle it will make with the bedding (θ). The greater the influence of shear, the larger will be this angle *at the beginning of deformation.* The effect of shear, however, is to rotate this plane in the direction of the shearing stresses, or toward the position which it would assume under simple compression, thus reducing the angle between it and the bedding. In incom-

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[1] LEITH, C. K., "Structural Geology" (revised), Henry Holt and Company, 1923, pp. 36, 37, 45, 46.

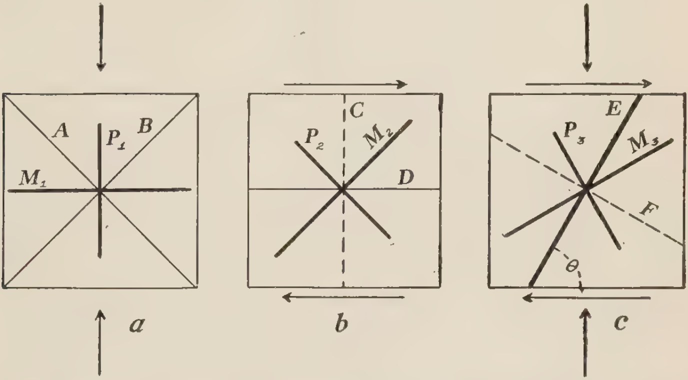

Fig. 101.—The effect of combined compressive and shearing stress:

M_1, M_2, M_3 and P_1, P_2, P_3, axes of elongation and of shortening under (*a*) compressive, (*b*) shearing, and (*c*) combined stresses.

A, B, C, D, E, and F: theoretical shear planes under the different stress conditions.

petent beds this effect may be very large, hence this plane may pass the position it would have assumed under simple compression, and approach parallelism with the bedding.

The plane E offers relief for both the compression and the shear (provided the shear planes are properly spaced). The tendency of the compression to develop plane A is counteracted by the rotation. The tendency for shear to occur along bedding planes is counteracted by the compression. Hence most of the movement will occur on E. If the compression is effective before the rotation, and A is developed, it may be opened as a fracture by tension parallel to M_3 when the rotation becomes the dominant force.

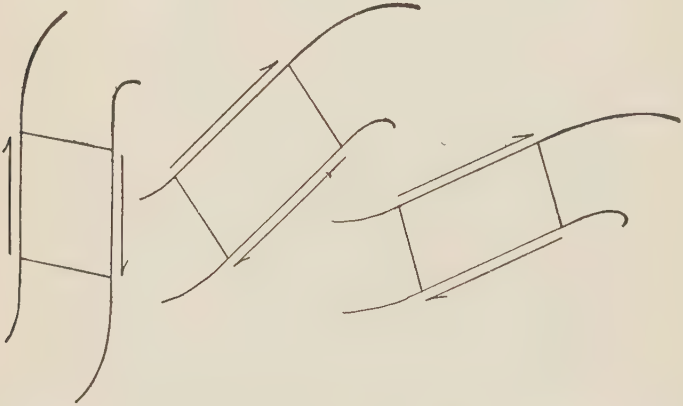

FIG. 102.—Normal limbs of folds, showing the position of shear planes developed according to the law of the strain rhomb.

In weak beds the force of compression is very effective, and the amount of deformation (rotation) may be extreme. Both of these factors reduce the angle made by the shear joints with the bedding, and this angle is therefore less in the weaker members of a series. It may be as small as 20 degrees in shale, between beds of sandstone where it is almost 90 degrees. In either case *the acute angles between the shear plane and the bedding point in the direction of the forces of the shearing couple.* This conclusion is of great practical value in determining the position of beds in folds, as in beds which occupy their normal position the shear joints will be more or less vertical, while in overturned beds they will be nearly horizontal (Figs. 102 and 103). The opposite is true of tension cracks which may develop on plane *A* in Fig. 101, or normal to the direction of elongation.

In the foregoing case one set of shear planes is developed on which practically all of the relief of stress is accomplished. This may be true under other conditions, particularly where relief may occur more easily in one direction along the axis of elongation than in the other. For instance, when the pressure is horizontal, and the direction of relief is upward, the shear plane which is inclined toward the direction of pressure is more apt to develop than the other, which is inclined away from it. In rotational stress in a horizontal plane the shear plane parallel to the forces of the couple is usually more prominent than the one at right angles to it, as is shown in Fig. 100. This subject will be discussed further under analysis of faulting.

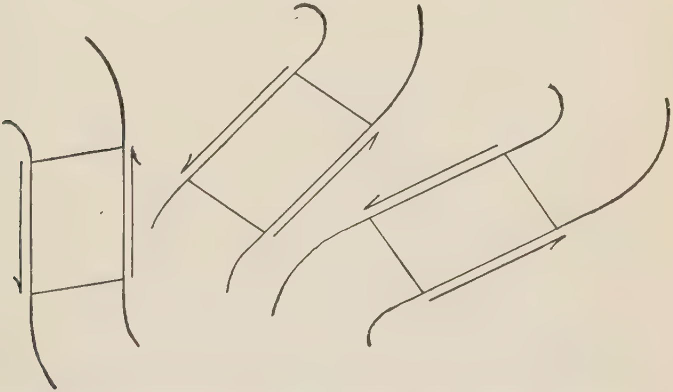

FIG. 103.—Overturned limbs of folds, showing the position of shear planes developed according to the law of the strain rhomb.

Spacing of Shear Planes.—The distances between planes of shear is determined by the law of least work. Relief of pressure will occur on the smallest number of planes possible to permit of the necessary movement. The factors which govern this condition are the strength of the material sheared, the confining pressures, and the amount of deformation. In certain cases the dimensions of the sheared mass are influential. The stronger the material the wider will be the spacing of the shear planes. The greater the confining pressures the less will be the relief on any one plane, hence the planes will be more closely spaced. The larger the amount of deformation the larger the number of shear planes necessary to accommodate it.

The effect of these factors is to increase the number of shear planes with depth. The deeper one goes, the larger are the confining pressures relative to the strength of the rock. Finally, as the zone of flow is approached, shear approaches microscopic proportions.

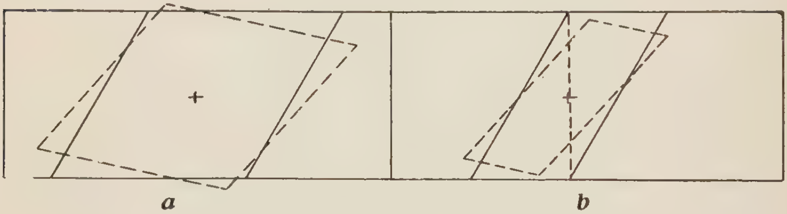

FIG. 104.—Spacing of shear planes.

a, Shear planes spaced too far apart to permit relief of vertical compression. Rotation of the block sheared out requires an increase in the vertical dimension.

b, Shear planes spaced to permit relief of vertical compression. Rotation of the block between them decreases the vertical dimension. The lower end of one is directly below the upper end of the next one to the left.

A case in which the dimensions of the sheared mass govern the spacing of shear planes is that of the shear in a bed on the limb of a fold. Becker [1] first stated the partial theory of the spacing of such joints, and Lovering [2] has quoted it to explain their development without recourse to the strain ellipse. The theory states that the joints or shear planes must be spaced closely enough so that the upper end of one joint (considering the bedding as horizontal) is above, or overlaps, the lower end of the adjacent joint. If they are more widely spaced an increase in vertical dimension is necessitated when movement on the joints occurs, and hence rotation of the blocks between the shears must take place. If they are spaced closely enough such rotation will shorten the vertical dimension, as may be readily seen by reference to Fig. 104. The determining factors are the inclination of the joint to the bedding, and the width of the bed or beds between planes of movement parallel to the bedding.

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[1] BECKER, G. F., Finite Homogeneous Strain, Flow and Rupture of Rocks, *Bull.*, Geol. Soc. Amer., vol. IV, p. 57, 1892.

[2] LOVERING, T. S., The Fracturing of Incompetent Beds, *Jour of Geol.*, vol. XXXVI, p. 716, 1928.

Curved Shear Planes.—In materials which do not offer uniform resistance to shear, shear planes curve toward the locus of least resistance. Thus a horizontal force may act through one mass against another mass which offers more resistance. The resulting shear planes in the first are diverted upward and may outcrop at the surface as vertical faults. Such faults are called *upthrusts*. If the compressive stress does not influence the rocks near the surface the shear plane may even pass the vertical and dip away from the direction of compression (page 289.) Compression through a mass of metamorphic rocks against a batholith illustrates the conditions necessary for the development of upthrusts.

A similar case is found in the slides along the Panama Canal. Here the compression is caused by gravity. Relief in a horizontal direction is afforded by the digging of the canal, but it cannot extend below the level of the canal. Thus the compressive force meets a resistance which it cannot overcome, and the shear planes are diverted into a horizontal position.

The difference in the angle made by shear planes with the beds in a series of varying competency is another case of the diversion of shear. As the line between the varying resistances is sharp, the shear planes change their angle abruptly, instead of on a gradual curve as in the first two cases.

Torsion and Shear.—The effects of torsion and shear on rocks are somewhat similar. Each has a tendency to produce two sets of planes (in the one case fracture planes, in the other shear planes) at approximately right angles to each other. This is especially true in nearly horizontal sedimentary rocks. Reference to Fig. 95 shows that, on a bed subjected to torsion, tension occurs in one direction on the upper surface of the bed, and at right angles to it on the lower surface. Tension cracks may form due to either of these stresses, and they may extend through the rock, producing vertical fractures at right angles to each other. A shearing stress acting in a horizontal plane also tends to produce two vertical sets of fractures. Fig. 105 shows a case in which either of these interpretations may be put on the structure. The material is hard, brittle chert. Two systems are shown, involving four more or less parallel sets of joints. The more continuous and better-developed joints (shown by the heavier lines) may be interpreted as shears due either to compression or to a shearing stress. The former

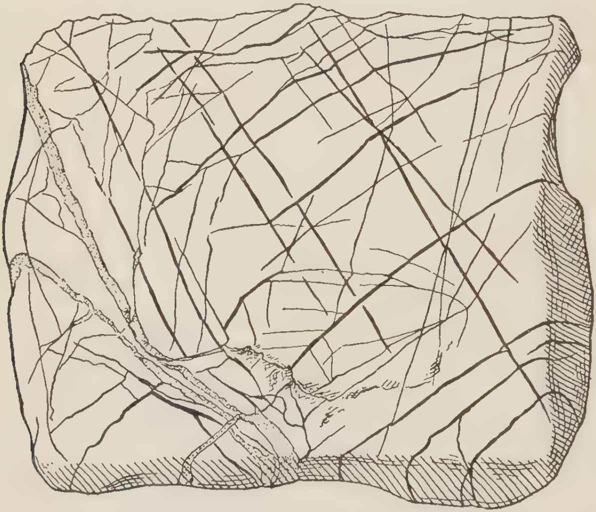


Fig. 105.—A piece of hard, brittle chert, which has been jointed by pressure. It is a type of deformation very commonly met with in the cherts of the intensely folded and faulted Franciscan formation of California.

would act either vertically or horizontally. The latter would act parallel to one or the other sets of joints. If the compression acted parallel to the short side of the specimen the vertical joints of the minor system could be interpreted as fractures developing at right angles to the direction of elongation. In this case the acute angle between the shear planes faces the compression. This is to be expected from the brittle character of the material. The explanation does not, however, account for the horizontal minor fractures.

If the systems are explained by torsion, the vertical minor fractures can be considered as tension cracks developed on the upper surface of the block, the horizontal minor fractures as tension cracks formed on the other side and only occasionally showing on the exposed surface. The diagonal or major joints may be due to the shearing stresses set up by the torsion. In such a case the compressional component would exceed the tensional one, as the shears are better developed than the tension cracks. Still another interpretation would be the opposite of this, that the major joints are tension cracks formed by torsion, and the minor joints are irregularly developed shear planes due to the less influential compressional component. The specimen offers a fine example of the difficulty of determining the actual stresses in a given case, unless evidence over a more extensive area is obtained.

ANALYSIS OF FLOW

Consideration of the conditions under which solid rock may flow belongs in another place. We are concerned here merely with the direction which the lines of flow produced thereby may bear to the stresses which caused the deformation.

The appearance of flow structure in rocks has already been described, and something of the process has been suggested. It is achieved by rotation of mineral particles so that their long axes are parallel and by recrystallization of original and development of new minerals, usually elongate in form, and also oriented with their long axes parallel to each other and to those of the rotated

FIG. 106.—Description. The specimen represented in this figure is a rod of green schist, which is long and rounded because the schistosity is fibrous and the transverse joints are spaced at long intervals. The form does not express the shearing rhomb, as that of the specimen shown in Fig. 115 does, but the process of development of the structure appears to have been very similar. The two rocks are alike in the relation of the transverse shears to the schistosity. They differ somewhat in the degree of development of the schistosity, which is greater in Fig. 106. The elongation in this case cannot be measured, but it may be estimated at several times the original length of the material by comparing the diameters of the fibers with their lengths.

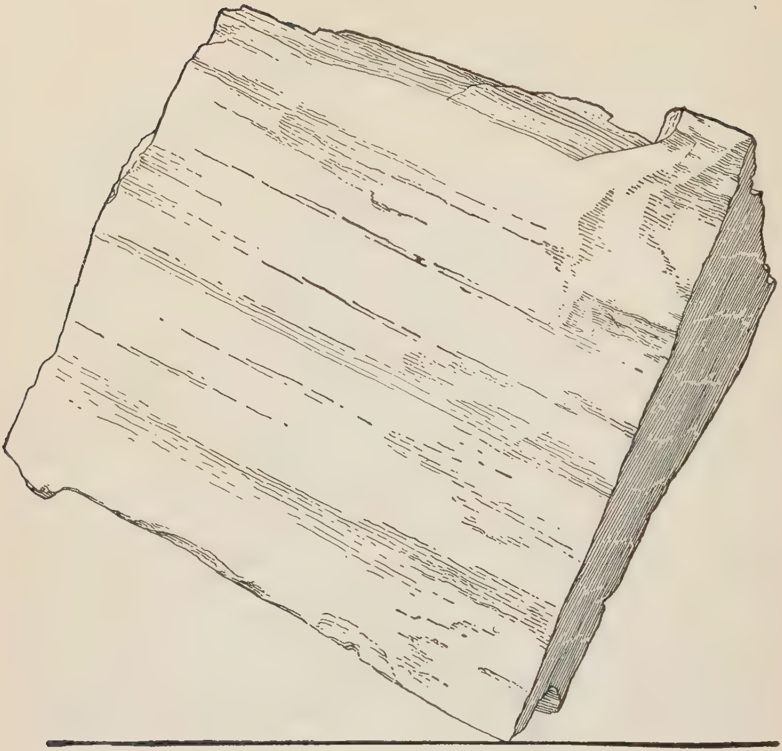
particles. The effect is to produce parallel banding of the rock, often associated with rock cleavage.

Three cases of nonrotational deforming stress may be considered. In the first, forces acting along the two lesser stress axes, that is, the resistances to deformation, are equal. The rock elongates in all directions at right angles to the deforming stress, producing a plane of extension on which flow cleavage is apt to develop. Cross-sections taken at an angle to this plane reveal the linear arrangement of mineral particles, but sections parallel to it show no such effect, as there is no differential stress to orient the particles.

The second case, that in which the forces acting along three axes are all unequal, is the commonest one in nature. The rock is elongated in one direction, that of least resistance. This by definition is the axis of elongation. It is shortened in the direction of greatest compression. It may or may not be elongated in the third direction, but in either case there will be differential elongation between this and the direction of least resistance, which will orient the mineral particles in the plane at right angles to the deforming stress. The result is a parallel arrangement of particles shown by cross-sections in any direction, and cleavage at right angles to the deforming stress (if the character of the rock permits its development) still less perfectly developed than in the first case.

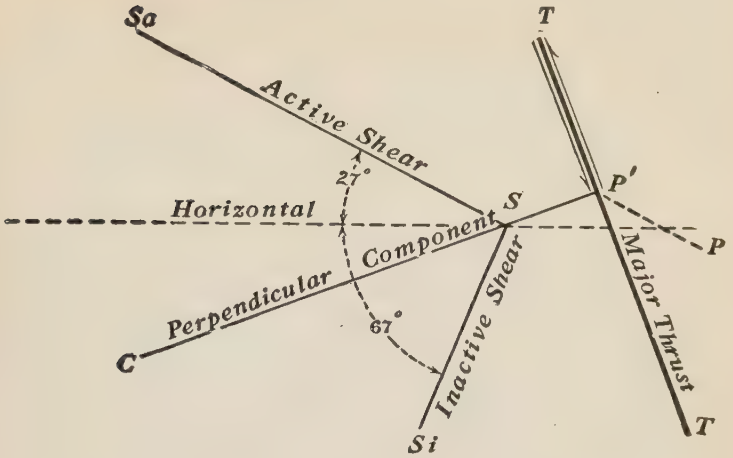
The third case is that in which relief of pressure occurs in one direction, and the stresses along the other two axes of stress are equal and both act to deform the rock. The rock elongates only in one direction, hence there is no tendency to form a plane of cleavage, but the rock may break up in pencil-like fragments. (Fig. 106.) Cross-sections at right angles to the direction of elongation (direction of least resistance) will not show the flow structure of the rock, as only the two smaller and approximately equal dimensions of the mineral particles are revealed.

Flow caused by rotational stress partakes of the character of the second stress system described above. In rotation the three axes of strain are different, hence the tendency is to develop a



a

Figs. 107*a* and *b*.—Description and Interpretation. The drawing represents a specimen of fibrous brucite from the Keystone magnesite quarry near Chewelah in the State of Washington. The mass of rock in the quarry is magnesite and dolomite from which it has been derived by hydrothermal alteration. The brucite is the product of intensive alteration on a vertical plane of transverse displacement. It forms a vertical sheet about eight feet thick and demonstrates the direction of displacement by striations, which run parallel with its fibrous structure. The specimen is oriented in the drawing in the position in which it stood in the quarry, with the fibers making an angle of 27 degrees with the horizontal. About 100 feet to the right of the specimen was the plane of a thrust fault of several thousand feet dip-slip, which had a dip of 70 degrees.



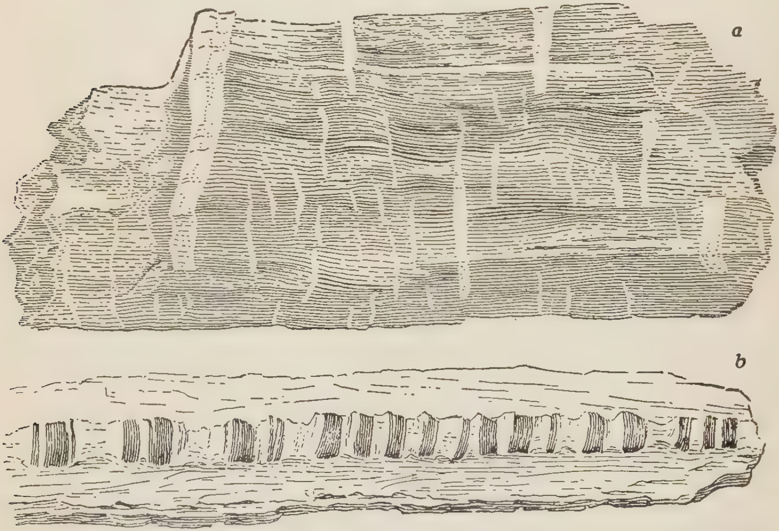
b

The diagram on the right of the drawing illustrates the relation of the thrust to the specimen and suggests a possible explanation of the stresses which induced the development of the fibrous structure and of the remarkably smooth joint planes at an angle of 94 degrees to it.

It is assumed that a force PP' acted against the thrust plane and caused the dip-slip displacement. The exact angle of incidence of the pressure does not enter into the problem. PP' was resolved into the components $P'T$ and $P'C$. Of these the former caused the dip-slip, while the latter developed two planes of major shearing strains, each at 47 degrees to its direction. One of these shears was directed downward and met with such resistance that there was practically no displacement, although the rock parted by shearing. The other shear was directed upward toward the surface, which was within a few hundred feet, and met with less resistance than was opposed to motion in any other direction. It therefore became the plane in which shear, mass-movement, molecular movement, and recrystallization met with least resistance, and they developed accordingly.

Ordinarily, under purely mechanical conditions of stress, the planes of shear parallel to the direction of least resistance would be spaced at intervals and the rock would break out in blocks. But the hydrothermal action penetrated the entire mass and produced the general alteration and fibrous structure.

linear arrangement in the direction of greatest elongation, modified by some parallelism in the line of the intermediate strain axis. Thus cleavage planes may be developed parallel to the line of elongation and perpendicular to the plane of rotation, but orientation of particles on the cleavage planes will still indicate the direction of extension.



Figs. 108*a* and *b*.—Illustrations of rocks which have been stretched by flowing. (After Heim, "Mech. der Gebirgsbildung," Plate XV.)

(*a*) Tension openings or tears in clay-mica schist, "Thonglimmerschiefer," filled with calcite.

(*b*) Segments of a fossil, a belemnite, separated by the extension or flow of the surrounding rock. The interspaces are filled with calcite.

Note that the tension cracks lie perpendicular to the direction of elongation.

The processes of flow and shear are intimately connected. Flow may even be described as microscopic or submicroscopic shear. Recrystallization plays an important part in it, and this may take place by gliding (shearing) on the internal planes of the crystals. Rotation of mineral particles is due to the shearing components of the deforming force. Finally those particles which are too nearly equidimensional to be rotated and are not capable of recrystallization often show tiny shear planes, oriented in intersecting sets in the correct position relative to the deforming stress.

It is possible in some cases to have flow structure, or cleavage which resembles it in the parallel arrangement of minerals, developed at an acute angle to the axis of greatest shortening. This occurs when one of the two sets of shear planes has become the dominant plane of movement in relieving the strain. The effect of continued movement in such a case is to produce minerals oriented parallel to the dominant plane of shear. An example which may be interpreted in this way is shown in Figs. 107, *a* and *b*. In this case the recrystallization may have been aided by mineralizers, or circulating waters, but the interpretation is still contrary to that usually put on such structure.

CHAPTER XI

ANALYSIS OF FOLDING

Competent folding analyzed: competency of different rocks, transmission of pressure, requisite of initial dip. Incompetent folds analyzed: size of incompetent folds, compaction folds. Factors which limit the depth of folding. Development of folds, symmetry and asymmetry. Relation of folding to external forces and to fracture, shear and flow: in compression, in horizontal rotational stress; en echelon folds, arcuate mountains, source of pressure. Development of composite folds. Depth of deformation determined by means of folds.

ANALYSIS OF COMPETENT FOLDING

Folds of very similar character may be produced by horizontal compressive stresses or by vertical forces or by a combination of the two. As a rule, however, the structures which are studied as folds, comprising anticlines and synclines and associated thrusts, are due to compression. They will, therefore, be discussed first under the head of that type of folding which is produced by horizontal stress, namely competent folding.

Competent folding is that folding of strata which is produced by compression in the direction of the undisturbed stratification, and which is conditioned by the requirement that a rising arch shall lift the load, or a sinking syncline shall displace the underlying material.

The usual condition is that the strata assume initially a nearly flat, horizontal, or gently inclined attitude, in course of the subsidence which accompanies deposition. They consolidate. They may become jointed at right angles to the bedding, in consequence of the warping or twisting due to subsidence. In course of time, it may be after long ages, they are subjected to compressive stress in the direction of the bedding. A fortuitous coincidence of the direction of force with the direction of bedding need not occur, for if the force makes a small angle with the bedding it will develop a powerful component in the plane of the latter and the effect will be the same as if the original stress had that relation.

Under these conditions a stratum is a strut, which is subjected to the shearing and bending stresses incident to its mechanical situation. If it be short and stiff, it may shear before it can bend. If it be rigidly supported below and confined by a sufficiently heavy load above, it also may shear before it can bend. But if it be of considerable extent in comparison with its thickness and be not too rigidly restrained above and below, it will bend rather than shear.

It is reasonable to assume that strata usually, if not universally, bend upward more easily than they can bend down, because the overlying load may be lifted into the air, whereas the foundation would have to be forced into the globe. Bending thus implies uparching and uparching implies lifting the load.

The load consists of the weight of the stratum itself and the weight of any superincumbent strata which do not lift themselves. It is possible to conceive a sequence of beds so nicely adjusted as to strength and flexibility that each one could just lift its own weight and would thus act independently of any of the others. But such an adjustment would be a surprising accident. In nature rigid sandstones are commonly associated with flexible shales. Strong, massive limestones are interbedded with thin-bedded strata of limestone and shale or sandstone and shale. The differences of flexibility and strength are very pronounced and the sequences very diverse. Weak beds are often *incompetent* to lift any appreciable part of the confining pressures. They perforce move passively. Strong beds, on the other hand, are *competent* to move the passive beds and carry up the weight of overlying strata. Uparching can occur only when there are strong beds, competent strata, capable of this lifting. This kind of folding is therefore called *competent folding.*[1]

In order that any stratum shall be competent it should possess certain inherent characteristics in a degree superior to that in which they are possessed by other strata. These qualities are (*a*) strength to resist shearing; (*b*) capacity to heal fractures; (*c*) inflexibility. On the other hand, the conditions which favor incompetence of strata in folding are (*a*) lack of coherent strength; (*b*) lack of cementing quality; (*c*) flexibility.

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[1] WILLIS, BAILEY, "Mechanics of Appalachian Structure," p. 247.

We may consider various kinds of sedimentary rocks with reference to these qualities.

Limestone is one of the strongest of the sedimentary rocks. Tests for crushing strength at the surface show a range from 11,000 to 30,000 pounds to the square inch. It is strongest in the metamorphic, crystalline varieties, and it shares the quality of great strength with slate. The strength may be attributed to the fineness of grain and the consequently numerous points of contact between the grains in unmetamorphosed limestone, and this effect is increased by the cementing action of calcite in the marbles.

Limestone heals readily. If a break occurs, the soluble substance of the rock itself cements the fissure and the cemented plane approaches or may exceed the original rock in strength. No non-calcareous rock has this quality in equal degree in the zone of folding.

Because of its great strength and because it usually accumulates in relatively thick, undivided beds, limestone is inflexible. It does not bend readily. When forced to bend it does so in major folds, in long curves, which conform to a uniformly distributed stress and consequently distribute the deformation in small adjustments throughout the mass. Among the adjustments, gliding on the cleavage planes of the calcite crystals is important, since such crystals are commonly very small and they provide a means of accommodation by innumerable, minute displacements without fracture.

The combination of superior strength, healing capacity, inflexibility, and adjustment by microscopic cleavage makes limestone the most competent among the sedimentary rocks in the zone of folding.

Sandstone is the symbol of rigidity,—and of weakness when broken. It possesses only moderate strength, about 0.8 that of limestone under confining pressure. It has no inherent cementing capacity. It offers no ease of accommodation by cleavage. It is thick-bedded as compared with shales, with which it is commonly associated, but is thin-bedded as compared with the great limestones. An individual sandstone stratum 100 feet thick is beyond the ordinary, whereas a limestone formation 1,000 feet thick is not uncommon. Sandstone lenses are often limited in extent and they grade out into interstratified layers of sandstone and shale, that is, into weak strata.

Because of its rigidity, sandstone in thick beds forms a strong strut, which transmits pressure, but if forced to bend it soon breaks or if held to the line of stress it shears irregularly. The broken segments retain their rigidity and in shales behave like a broken bone. Sandstone is therefore in the zone of fracture where shales and even limestone are in the zone of folding. Although locally very competent, it rarely affects the form of large structures, such as are controlled by massive limestones.

Shale varies in its relations to folding according to its constitution. Sandy shale is brittle, like sandstone. Argillaceous shale is tough and plastic. Calcareous shale is less plastic, but has the quality of recementing itself by the crystallization of calcite. None of the varieties has sufficient strength, however, to overcome the weakness caused by the flexibility which is due to the very thin bedding. It was observed by Heim that shales accommodate themselves to the folds assumed by more competent strata, or to the spaces within such folds; that is to say, they are incompetent, as a rule, to act for themselves or to control the action of other strata.

Shales nevertheless form very large and regular folds when they occur in thick and extensive masses. Thus the Devonian of Pennsylvania, which is a large delta deposit of sandy shale and thin-bedded sandstone 8,000 to 10,000 feet thick, lies in very broad and simple folds, and, while the control was probably in the very massive, underlying limestone, the accommodation within the Devonian was facilitated by the somewhat uniform distribution of competency in the beds of shale and sandstone. Within the

Devonian there was an approach to individual competency in each minor stratum.

With reference to relative competency to control folding we may class massive limestone formations as most competent to control large structures, sandstones as locally competent in minor folds, but liable to fracture, and shales as incompetent.

In any anticline in which different kinds of sedimentary rocks are involved, there are always stronger and weaker formations. The differences of strength may be very decided or relatively small. Where limestones, sandstones, and shales occur in thick deposits, they will commonly differ greatly in strength, and it is in such sequences that the typical structures of folded mountain ranges are developed. Often there is one formation, usually a thick limestone, which is *the* competent stratum of the series. Again, there may be a thick series of interbedded shale and limestone, or of shale and sandstone layers, which presents a certain uniformity of competency within its total thickness. A thick, argillaceous shale is the weakest, as a thick, massive limestone is the strongest of all stratified formations. These differences of competency materially affect the character of folds and of different parts of folds.

In the course of development of a competent anticline, the stronger formation tends to lift the overlying load. If it be fully competent, it will lift the whole load over its arch. If it be but partially competent, it will lift only part of the whole and must be assisted by adjacent strata if a competent structure is to develop. It may happen that a shale is not competent to raise and sustain even its own weight over the full span of the arch of a competent limestone. There are thus all degrees of competency, which depend not only on the nature of a particular formation, but also on the relative strength of the adjacent formations, as well as on the span of the anticline.

We may next consider the effect of competency on the manner of folding within the competent arch and over it. The difference is marked if there be one formation which is notably more competent than the strata below and above it.

Since a competent anticline lifts the load, the section of strata within the competent arch must be relieved of load. And since there are all degrees of competency, the proportion of load lifted may vary from the whole to a small fraction. Whatever be the degree of competency, there must be *relief from load within a competent arch, under the competent stratum.* The effect in extreme cases may be to develop an open space. The underlying strata then come into the zone of fracture and are often broken, crumpled, and confusedly overthrust. A common result of partial relief is the well-known thickening of strata on the anticlinal axes (Fig. 29).

Above a competent formation in an anticline, the strata are subjected to an upward push from within. They are thus stretched over the arch. They may simultaneously continue to share in the compressive stress exerted in the direction of the stratification. The resultant stress may be one of more moderate compression or one of tension, according to the preponderance of one or the other of the opposed forces. The tensile stress will bear a relation to the relative competency of the lifting and lifted formations, being greater in proportion as the difference in competency is greater. The compressive stress will be weaker as the overlying strata are relatively less competent. Thus a weak shale, overlying a decidedly competent limestone, may be subjected to a definite extensive or spreading stress. Under sufficient superincumbent load, it may shear under vertical stress, suffer normal faulting, or squeeze out and become thin. An overlying sandstone may exhibit open, vertical fissures.

The effect of these relations on the forms of folds under a competent stratum and over it is very marked. Under it the effects of compression are intensified. Over it they are lessened or replaced by extension.

The competent stratum, rising from the underlying formation, transfers the load which it lifts from the axial region to the limbs of the folds. In them the strata are firmly held to parallelism, are often straight, and may be thinned by excessive pressure, while they thicken on the axes. The resulting fold in the competent stratum is of the type which is called *similar*, because the limbs

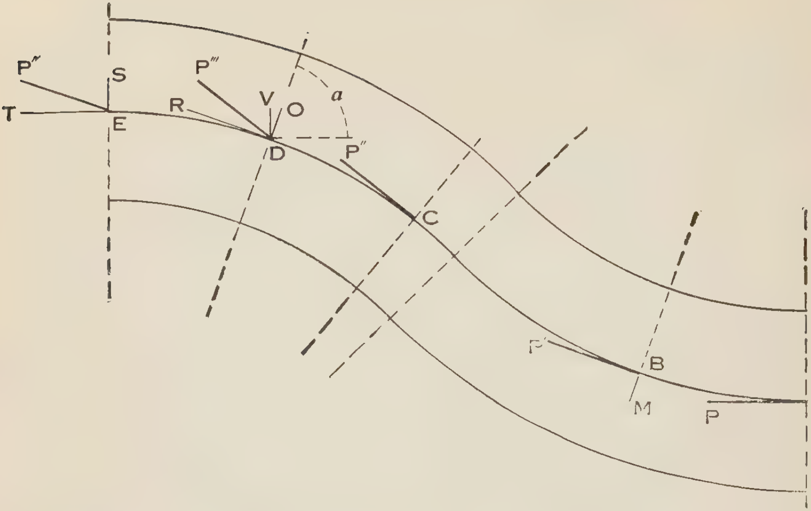

FIG. 109.—Development of stresses in a competent fold:

Let it be assumed that an incompetent fold has developed to the curve *ABCDE* and that it is subject to a horizontal force *P*. Assume further that the surface *ABCDE* is a bedding plane and one on which movement may take place. Let the system of forces in all directions be in equilibrium, so that there is no motion and no work done, but let the resistance to shear be greater than that opposed to flexure, so that an increase in the value of *P* will cause the anticline to rise as a competent structure.

Under the assumption of equilibrium, the pressure *P* will be transmitted along the surface *ABCDE*, everywhere tangent to the curve and everywhere opposed by an equal resistance. If there is no movement there will be no loss, and *P* will everywhere along the surface *ABCDE* have the same value in the direction of the tangent. P' and P'', for instance, will be equal.

Let the assumed state of equilibrium be interrupted by an increase in the pressure *P*, in a gradual manner so that the rising pressure is the same throughout the length of the comptetent stratum. Then, as motion ensues on the surface *ABCDE*, the pressure *P* will be resolved into components perpendicular and parallel to *ABCDE*. Considering any two adjacent, minute elements of the curve as straight lines, the direction of pressure in the one nearer *A* is a tangent to the curve and diverges from the direction of pressure in the one toward *E*, by an angle equal to the angle between their respective radii.

In order to visualize the resolution of forces, assume that *C* and *D* are points immediately adjacent and may represent the minute elements referred to. Take DP'' equal to and parallel to CP''. Then the components *DO* and *DR* are active in the radial and tangential directions respectively.

The radial component *DO* owes its existence to the curvature of the bed, and depends for its value on this curvature. If the transmitted pressure remain the same *DO* increases if the curvature increases. In this case the curvature has been assumed to be uniform from *C* to *E*. Hence *DO* will not vary through this arc.

It would appear that the force DP'' would diminish at E to one equal to DR, but as there is no motion, DO is balanced and offset by the external resistances, which thereby deflect DP''' to BP^{IV} without loss.

If the direction of least resistance is vertically upward, the vertical subcomponent DV of the radial component DO will be the effective force to produce motion, and this motion will first occur where it first becomes greater than the weight opposed to it.

Now the value of DV, expressed in terms of DO, is DO sin a; a being the angle made by DO with the horizontal. If DO does not vary between C and E, that is, if the curvature is uniform, DV will be a maximum when the angle a is 90 degrees, that is, at the top of the arch. The lifting tendency will therefore become effective at the crest of the curve, at E.

Before any motion can occur, however, the competent stratum must be bent upward. This requires that a certain length of the stratum be raised, since the slab cannot bend unless its length in the direction of the arch be several times its thickness. The radial components along a portion of the curve, from E back to C for instance, must therefore grow strong enough to lift the load and to bend the competent stratum. This, under the assumed conditions, will result from a sufficient increase in the value of the original pressure P. When that pressure becomes adequate to develop the necessary radial components, the arch will rise as a competent anticline.

When uplifting begins, work is done and the radial components subtract from the successive pressures transmitted from element to element of the curve. The effect must be to diminish the transmitted pressure to a value at which it can no longer develop a competent radial component. Thus the distance to which the transmitted pressure may continue to be effective is limited.

The condition which determines the proportion of any radial component to the pressure transmitted to the corresponding point of the curve is the degree of curvature. The sharper the curve, the greater the radial component and the more rapid the exhaustion of the transmitted pressure. In the hypothetical case employed to develop the mathematical relations, the curvature was assumed to be uniform. In nature it would rarely be so, or if uniform while the anticline remained incompetent it would commonly become nonuniform as the competent structure rose under unequal resistances. Wherever the curvature originally was or later became sharper, the radial components would absorb a larger proportion of the transmitted pressure and, assuming the latter to be the same in adjacent sections, the arc of sharper curvature would rise faster.

The preceding holds true for those stages of development during which the dips are low. Those shown in Fig. 109 are much steeper than the initial dips in which competent folds probably begin to grow. In experimental work it has been found that a deflection of one degree, or even less, was sufficient to fix the position of a competent anticline. Competent folding probably begins, therefore, with very gentle dips; that is, in an attitude in which the radial component is but a very small part of the transmitted pressure.

It is evident that, just as the radial component has a vertical sub-component, so the tangential component has a horizontal sub-component. The latter lies in the competent stratum so long as the dips are low and exerts a shearing rather than a bending effect. But as the dips grow steeper, the bending effect increases in importance, with the result that the limbs of the fold are pressed together under the crest.

By an application of the principles deduced in the preceding paragraphs, the various types of folds: symmetrical or unsymmetrical, acutely arched or flat-topped, carinate or fan-shaped, may be explained as developments of competent structures.

of the anticline make the same angle with one another in different strata. The axial regions are correspondingly thickened.

Above the competent stratum, on the other hand, the lifted strata must conform to the uparching mass. They will tend to be parallel to the upward convex curve and among themselves. The type of fold which is thus developed is characterized by the general parallelism of the strata throughout and is therefore called *concentric*.

Similar and concentric folds have been distinguished in the descriptions of folds. It is obvious that they represent different mechanical effects and should be discussed as distinct effects, whether the discussion deals with the theory of folding or treats of its application to problems of an economic nature.

Turning now to the consideration of the transmission of pressure in strata undergoing folding, we recognize that the fact of folding having been initiated implies that the alternative phase of deformation by shear was more difficult and was therefore replaced by bending. In order that a pressure should bend a stratum it must have a component at right angles to the bedding. Under the assumption too commonly made, that the strata were flat and horizontal and the force was also horizontally directed, no such component could exist and no folding could take place. Evidently the stratum or the force or both must be inclined to the horizontal, so that the force impinges upon a bedding plane at some acute angle. When this is the fact, we have the simple case of a force acting against an inclined plane (Fig. 109) and the resolution of the principal force into two components, one at right angles to the plane and the other parallel to it.

Let us assume a sequence of strata already bent at some line and subjected to a pressure which coincides in direction with the bedding on one side of that line. Then the direction of initial pressure will be inclined to the bedding beyond the line of bending. The initial pressure will therefore be resolved into two components, each of them smaller than the original. Deflection of the strata, if it occur at all, will be caused by the perpendicular component, while the parallel component will be transmitted in the strata in the direction of the bedding beyond the bend.

If the strata are continuously curved, the resolution of forces must occur at each element where the bedding changes direction. At each resolution the force transmitted in the direction of the bedding is reduced by an amount proportioned to the square of the deflecting component, until finally it is diminished to a relatively weak stress that is no longer capable of causing deformation. We thus reach the conclusion that no effective stress can be transmitted through an actively developing fold.

This conclusion does away with the necessity of assuming that any particular fold or a zone of folds must be buttressed on one side by an immovable mass, which opposes its immobility to the active pressure from the other side. In order that horizontal compression should cause folding, it is necessary, but sufficient, that there should be an initial bend or dip, adequate to develop an effective deflecting component. Such an initial dip may originate through downwarping or upwarping of the sediments, and it is demonstrable from the inequalities of thickness of sediments that deeply buried beds must have subsided so unequally as to be bent and warped initially. We are thus led to a conclusion which has an important bearing on the location and development of folded zones and mountain ranges.

Strata accumulating in a subsiding trough may be warped by unequal subsidence in such a manner that they acquire an initial dip or change of dip. This can hardly fail to occur where the deposits cover the zone between an area of subsidence and one of uplift. The more deeply they are buried, the greater the probability of warping and the more acute the probable change of dip. In deeply buried strata consolidation is advanced and the differences of competency are emphasized. Therefore, when such strata, so situated, are subjected to adequate horizontal pressure, they yield by competent folding. In the development of any fold, the force which is active in the competent stratum is exhausted in producing the uplift. Deformation of any area situated beyond the fold can occur simultaneously only through the action of a stress transmitted through rocks below the competent stratum, or subsequently when the competent fold is closed and transmits the pressure as a rigid mass.

This purely mechanical result explains why great depressions in the earth's surface, which become filled with sediments, the so-called geosynclines, are commonly raised in the form of folded mountain ranges. The question is not appropriate to this place, but will be discussed more fully in that part of the work which deals with the current theories of deformation.

ANALYSIS OF INCOMPETENT FOLDING

Incompetent folding differs from competent folding in the direction of the deflecting stress and in the character of the resulting tension. As has been stated in the preceding section, competent folding is produced by pressure directed in the planes of the strata, when they are in a nearly horizontal position, and resolved into components parallel to and perpendicular to the beds as they bend. Since the angle which the pressure makes with the bedding is an

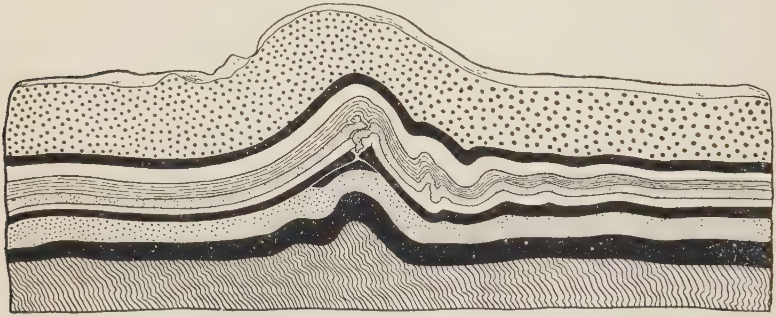

FIG. 110.—Section of model demonstrating the effect of competent folding. The model, composed of strata of wax and wax mixed with plaster, was compressed from right to left. The upper bed (dotted) was competent and lifted the load. Weak strata within the arch were thrust into the area of relief of pressure and there crumpled.

See "Mechanics of Appalachian Structure," *Thirteenth Annual Report*, Plate LXXVIII.

acute angle, the component parallel to the bedding is larger than that perpendicular to it. The folding mass, considered as a whole, is subject to tension in a vertical direction, as is demonstrated by the spreading in the axial planes of similar folds. Competent folding, therefore, is characterized by horizontal compression and vertical extension.

Incompetent folding is the result of a deflecting pressure which is initially directed at right angles to the strata, or nearly so, when they are in a horizontal or gently inclined position, and which also is resolved into components at right angles to and parallel to the stratification. But, since the angle which the direction of the stress makes with the bedding is a high angle, the perpendicular component is larger than the parallel component. Hence, it follows that the mass as a whole is subjected to vertical, or radial compression and to horizontal, or tangential tension.

Incompetent is a necessary preliminary to competent folding. The radial component cannot develop unless the strata have already been deflected from a flat plane and that deflection is incompetent flexure. Initial deflection occurs as a result of subsidence or uplift, or both, acting simultaneously on adjacent areas of buried strata. Theoretically, horizontal compression may or may not affect strata so situated, but it is a fact confirmed by general observation that it often has done so, and with sufficient power to cause competent folding, when sediments have accumulated to great thickness in a geosyncline.

The area of an incompetent flexure may be very extensive, as extensive as a continental plateau or an oceanic deep, or it may be long and relatively very narrow. In the same mechanical class we may place laccolithic domes, although they are genetically distinct. The essential fact in the development of an incompetent fold is that there has been subsidence in response to the attraction of gravity or there has been uplift due to one or another of several kinds of up-pushing. We may review the various conditions to which incompetent folding may be attributed, but without going into the theory of their origin in this analytical treatment.

Whatever the deep-seated causes may be, subsidence is a movement which affects very large areas of the earth's surface. Gravity is the evident and sufficient force. Subsiding areas are the gathering places of sediments, both continental and marine, and the earlier deposits, in course of subsidence and in consequence of subsidence, become deeply buried under the later ones. It is demonstrable that the earlier beds were practically flat when deposited, that the thicknesses of the overlying strata vary greatly over the area of deposition, and that the upper surface was also practically flat during and at the close of the process of accumulation.[1] There is, therefore, no escape from the conclusion that the older formations became flexed or warped during the progress of subsidence and in consequence of the vertical attraction of gravity. The structure thus developed is, by definition, an incompetent syncline. It is already well recognized as the "geosyncline" of Dana. It is not limited in occurrence to continental, marginal, or marine areas, and may be represented by the geosyncline of the Alps, by that of the Appalachians, by the basins of the Rocky Mountains, by the Valley of California, or by the Caribbean deep.

The converse of the geosyncline is the "geanticline," an upfold of similar dimensions. As an illustration we may cite the present elevation of the Appalachian Mountain region, a broad, low dome, 1,500 miles long and 600 miles wide. Exception might be taken to this example on the ground that it had never been covered with sediment and therefore could not be regarded as a flexure in strata, and strictly speaking the objection is valid; but the citation may stand to call attention to the very close relation which exists between incompetent flexures in strata and upwarps of deeply eroded areas, although in the latter the form can be traced only in a flexed peneplain.

The incompetent geanticline is better represented by an elevated plateau region covered with marine sediments, since in such a structure, as for instance in the Colorado Plateaus, the flexures and faults may be traced out in the strata. The very low dips, the very broad uplift cannot be attributed to horizontal compression applied to the strata themselves, but must be regarded as the effect of a general up-push affecting the entire area from below.

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[1] Willis, Bailey, "Mechanics of Appalachian Structure," Plate LXIX.

Turning to the consideration of smaller structures, we may class as incompetent anticlines the covering of batholiths and laccoliths. The strata in these relations have been bent upward by the intrusion of molten masses below them. The force exerted is radial upward and outward, at right angles to surrounding strata. The structure is, therefore, by definition, an incompetent anticline.

We have seen that in the development of a competent fold there is a distinction to be made between the activity of the competent stratum and the passivity of the incompetent beds. The latter are bent over the arch of the former by reason of the up-push of the competent anticline beneath them, and it follows that the upper or incompetent beds assume the character of an incompetent anticline. Competent and incompetent structures are thus associated in the growth of folds produced by horizontal compression.

Where the crystalline basement beneath a more or less heavy blanket of sediments is displaced, the strata must suffer a corresponding flexure of the incompetent type. The displacement of the foundation may be due to gravity and be subsidence of the kind already discussed, or it may be in the nature of an upthrust. The latter is not uncommon in certain regions where a metamorphic sub-structure is under great compressive stress, as it is for example in the Coast Ranges of California. An upthrust fault, originating in the basement rocks and becoming active after a period of sedimentation, will lift the overlying strata on the edge of the upthrust block. The effect is to produce an unsymmetrical anticline, which, if it develops far enough, may pass into a normal fault. The strata, being stretched over the upthrust block, are in a state of tangential tension peculiarly characteristic of incompetent folds. Where anticlines occur in unconsolidated sediments overlying a crystalline basement, especially in regions where upthrusts are common, this type of incompetent fold may reasonably be inferred. Certain of the oil fields of the San Joaquin

Valley exhibit illustrations, in which the Pliocene and Pleistocene formations are arched in long, narrow folds.

The mechanical effects of incompetent flexure are those peculiar to tangential tension, resultant normal faulting, and incidental crushing with minor compression features. Shales are fissured, loosened by horizontal extension, and thinned by normal faulting. Sandstones are jointed and the radial joints are opened. Limestones also are jointed, but the many minute fissures are not infrequently sealed by the deposition of calcite. Joints and normal faults tend to develop as strike joints and strike faults, with less pronounced jointing or faulting across the axis of uplift in domes or cigar-shaped folds.

Development of incompetent flexures in sediments during deposition has been found to be common in many regions. As oil and gas may accumulate on anticlines with very gentle dips, they have in many cases been carefully drilled and accurate measurements of the varying formations have been secured. The sediments are frequently thinner over the axes of the anticlines. The thinning may be due to lack of deposition in relatively shallow waters and swift currents or to unequal settling. It is often demonstrated that there is an older anticline underneath the thinner zone in the younger strata or that a buried ridge occupies that position. This fact suggests that the buried mass may have been rising during deposition. It is also suggested that the strata may have become more compact over the ridge. Nevin and Sherrill [1] have studied the effects of these factors experimentally, and have suggested the term *compaction fold* for this type of structure. This term serves a certain use, though it implies that compaction is the principal if not the only factor in their formation, and a more significant one is desirable. Such folds are not confined to the gently dipping sediments of such areas as the Midcontinent oil fields, but are also found where the folding is quite intense, as in the California Coast Ranges.

Evidence has been advanced to show that oil will accumulate in anticlines only when they are formed during or soon after deposition of the oil-bearing sediments. A study of the oil fields of the United States reveals that in many districts the sedimentary section is thinner over the anticlinal axes. An application of this criterion to the determination of the age of folding may therefore be of considerable economic importance.

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[1] Nevin, C. M., and Sherrill, R. E., Studies in Differential Compaction. *Bull.*, American Association Petroleum Geologists, Vol. 13, pp. 1–22, 1929.

Persistence of folding on the same axis through different periods of deformation may produce a structure similar to that described above. In the California Coast Ranges deformation, uplift erosion, and deposition were simultaneous throughout the Tertiary. Folds were formed, their tops were eroded, new sediments were laid down over them, and folding was renewed. The resulting unconformities within the folds give the appearance of varying thickness of the formations. In many cases it is possible to prove that both are present.

DEVELOPMENT OF FOLDS

In the prevailing loose use of the term folding, the development of both incompetent and competent folds is included. The similarities of form and the intimate association of the two types justifies the usage, even though they differ markedly in the mechanics of growth. But, in order that we may clearly understand their relations, it is desirable to trace out the development of the structures.

In its initial stage any fold must be of the incompetent type. Its deflection progresses with subsidence during the deposition of the strata in a geosyncline, resulting either in a broad, simple syncline or in synclines and anticlines in alternate pairs. The original distribution of these incompetent folds may be determined in any basin where the beds are exposed to view, by measurements of the variations of thickness. Observations are less numerous than would be desirable for a generalization, but the evidence at hand indicates that, as a rule, the initial, incompetent flexures are convex upward as well as downward, as would be expected since irregularity of subsidence is more probable than regularity.

During the progress of subsidence, the forces which deflect the strata are essentially vertical. The downward movement is in response to gravity, and any up-arching is due to the lagging behind of that section as compared with adjacent sections. In order that competent folding should ensue a horizontal stress must become effective, and this may come about through any one or a combination of several conditions:

(1) If the geosyncline be subject to horizontal stress from the surface down to an indefinite depth during the process of deposition, then competent anticlines will begin to develop from the incompetent arches when the curvature of the latter becomes sufficient to give the radial components adequate lifting power.

(2) If the geosyncline be subject to horizontal stress only in deeper horizons during the progress of deposition, then competent anticlines will begin to develop only when strata which are adequately bent sink to that depth, or when strata which have sunk into the zone of compression become adequately bent.

(3) If the subsidence of the geosyncline be not contemporaneous with the existence of a compressive, horizontal force, the structures of the geosyncline will continue to develop as incompetent flexures until such time as the sufficient force of compression may arise.

There is good reason to believe that all three of these cases have occurred in the course of the history of the various folded regions of the earth.

In the evolution of competent from incompetent folds, it is probable that anticlines first become competent, before synclines, since uplift must commonly be easier than forcible depression. Uplift requires that the radial component shall be adequate and that the rock shall be strong enough to lift the overlying load. The former is a function of curvature, a sufficient original stress being assumed, and the latter depends upon the nature of the rock and the thickness of the strata. These points have been adequately covered in the preceding section.

The form of the competent fold will depend upon that of the incompetent flexure and upon the manner of application of the compressive stress. To illustrate we may consider certain cases.

Let it be assumed that the incompetent flexure is a symmetrical anticline with a uniform curvature throughout. It consists of three elements: the first (that toward the origin of stress) is concave upward, and extends to the inflection point. The second is convex upward, and extends across the axis to the second inflection point; the third is again concave upward. If the curvature is uniform, the level of the horizontal portions of the stratum is the same on each side of the fold. As we are dealing with earth forces, we will proceed most consistently by assuming that the growth of the compression has been gradual enough to affect the entire length of the fold. The stress transmitted by the competent bed, therefore, will be uniform throughout its length before movement due to the compression occurs. Since the curvature is uniform, the radial components of stress (which are functions of the curvature) will be uniform. It is these components which must cause increased curvature, or movement at right angles to the bedding. They will do this first where the least resistance is opposed to them. Those in the first and last elements of the fold press the bed against the underlying mass. Those in the element which is convex upward tend to lift the overlying load. As the direction of least resistance is directly upward, relief will first be found on the axis of the fold.

As soon as movement occurs, however, the stress conditions are changed. Work is done which uses up some of the effective force applied at the end of the competent stratum. Hence the stress transmitted by the stratum will not be so great on the axis as nearer the source of active pressure, and the maximum lift will be shifted from the axis onto the limb toward the source. The effective force of deformation will be localized at the point of inflection. This effect is counteracted in part by the increased curvature on the crest, which tends to increase the radial component.

If the force of compression comes from one side of the fold only, another effect of its dissipation by the accomplishment of work is seen. The incompetent fold was assumed to be symmetrical. At the beginning of movement the force in the limb toward the compression is opposed by an equal force in the opposite limb. As the movement proceeds, however, the compression is dissipated, and this resistance falls off. The arch between the inflection points is now acting as a unit. It will continue to lift the load, since by definition of a competent fold it is able to do so. The forces acting on it, though, at the two points of inflection, are no longer equal, hence their resultant will no longer be vertical, but will be inclined toward the origin of compression. As the ultimate resistance is applied in the line of the competent bed beyond the fold, this produces a rotational stress which tends to steepen the dip on the inactive limb of the fold, and to force the arch and the active limb over it. Thus an unsymmetrical competent fold develops from a symmetrical incompetent fold, where the force is applied from one direction only. *Other conditions being equal*, the axial plane of the unsymmetrical fold will dip toward the origin of the deforming force. A fine example of the development of such a fold is found in Plate C, *a*, *b*, *c*, and *d*, Appendix III.

It is obvious, though, that if the force is applied equally from both directions at the same time, the stresses at the inflection points will be equal, and the resultant will remain vertical, thus forming symmetrical competent folds from symmetrical incompetent folds. Cases where this may occur will be discussed shortly.

Where the incompetent fold is unsymmetrical, a rotational stress is produced at the start of deformation between the active force and the resistance (if the stress comes from one direction only) or between the two opposed forces. This will cause rotation of the axial plane in the direction of rotation of the couple, and will produce unsymmetrical competent folds in which the axial plane is inclined in the same direction as that of the unsymmetrical incompetent fold from which they develop. An example of this kind is shown in Plate E, Appendix III. Here the unsymmetrical character of the incompetent fold is sufficient to overcome the tendency of the competent fold to overturn away from the source of the pressure. If thrust faults develop from folds in such a case they are underthrusts rather than overthrusts. In Plate G the axial plane of the incompetent fold is inclined away from the source of pressure, and the initial development of the competent fold retains this condition, but the effect of the active force is sufficient to rotate the fold back into a position approaching symmetry.

It is noteworthy that in the Appalachians nearly all of the folds are overturned to the west. This fact can hardly be regarded as accidental. The few cases of folds overturned to the east have been analyzed and explained on the ground of assymetry of the incompetent fold from which they developed. The dip of the strata in the geosyncline before deformation must have been prevailingly eastward, as the sediments are much thicker in the eastern portion. This would tend to produce folds overturned to the east. The prevalence of the opposite condition, therefore, is strong evidence to indicate that the active force was applied from the east. Definite confirmation is found in the lessening of the intensity of deformation westward through the folded zone.

Relation of Folding to External Forces.—A common conception of the force which produces folding is that of horizontal compression, acting on strata from one direction, without rotation. Usually only the central portion of the deformed mass is considered, and the possible relations of stress and strain at the ends of the belt of folding are neglected.

Leith and Mead [1] have shown experimentally that folding can also be produced by a shearing stress acting in a horizontal plane in the basement rocks beneath the strata.

In nature examples of each of these modes of folding are found, as well as cases in which the effect is a combination of the two. The latter range through a great variety of effects, from conditions approaching simple compression on the one hand through those of simple shear to those where the dominant force is one of tension, yet where slight rotational stress has produced folding.

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[1] Leith, C. K., "Structural Geology," revised. (Henry Holt and Company) 1923, p. 190.

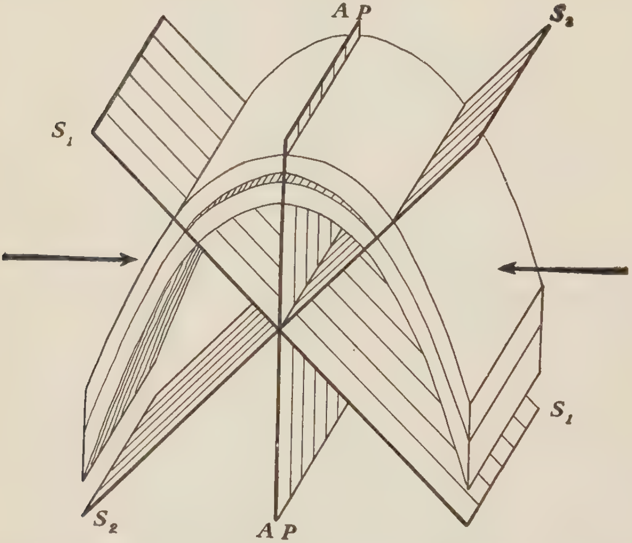

FIG. 111.—A fold developed by simple compression, showing the position of the planes of shear, S_1 and S_2, in relation to the axial plane, AP. The latter is the plane in which flow develops if deformation is sufficiently intense. The development of fracture normal to the direction of least resistance is shown by the spreading of the beds on the axis of the fold.

Folding Due to Compression.—The relations of the stress and strain axes in folding due to simple horizontal compression are easily understood. They are shown in Fig. 111. Shortening takes place horizontally parallel to the compression. Relief is easiest upward, and in folding the vertical dimension of the mass is increased; hence, so long as the folds remain symmetrical, this is the axis of elongation. It is parallel to the axial plane of the fold. If, however, the fold becomes unsymmetrical, as explained on page 264, a force couple is formed which rotates both the axial plane and the axes of strain forward with the movement of the fold. *In any case the axis of elongation remains parallel to the axial plane of the fold.* It should be noted that this rotation is a result of the internal stresses in the folded strata, and does not imply a change in the direction or character of the external force.

The third strain axis is horizontal, at right angles to the compression. There is no dimensional change along it, and this axis is therefore inactive under the conditions assumed.

Shear, fracture and flow assume their correct positions relative to these three strain axes. Shear planes may develop at angles of 45 degrees to the horizontal, with strike parallel to the axes of the fold, and dipping in either direction. If movement on these becomes measurable, as is frequently the case, they pass into thrust faults, and they are overthrusts or underthrusts, depending on whether they dip toward or away from the compression. The shear joints found on the limbs of folds are similarly oriented.

Normally fractures form at right angles to the direction of elongation. In the case of folding they therefore would lie in a horizontal plane and would be opposed by gravity; hence there is little likelihood of their development. Underneath the competent stratum, however, on the axis of the fold, stress may be relieved sufficiently to form an open space. If this occurs this space is properly oriented in relation to the strain axes.

Fractures at right angles to the bedding in the incompetent beds above the competent bed are related to a local system of stresses. They are formed by tension over the arch, normal to the axis, due to the lifting effect of the beds below. If the external force of compression which causes folding is active in the upper beds, such tension cracks are not formed.

Flow may develop in beds which are being folded at great depths. Its normal expression is found in thinning of beds on the limbs and thickening on the axes of the folds. This may occur in soft beds before typical flow structure, due to parallel orientation of mineral particles, is developed. When it does develop, under conditions of extreme pressure and deformation, it is oriented at right angles to the axis of shortening; hence it is parallel to the axes of the folds. This statement is borne out by observation, and it offers an extremely valuable criterion for the interpretation of complex and closely compressed structures, as the flow structure seldom varies over a few degrees from this ideal position.

Minor folding is very apt to occur in connection with major folding. It is produced by the shearing stresses set up within a fold by the relative movements of beds along bedding planes, or by the crushing of incompetent beds under the arch of the competent bed. The former is called *drag folding*. In either case the axial planes of the minor folds are essentially parallel to that of the major fold, and the positions of the two correspond even to the plunge of their axes.

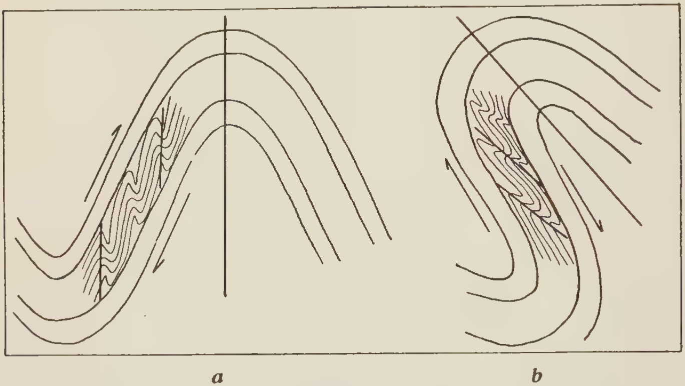

FIG. 112.—Normal and overturned limbs of folds, showing the position of drag folds. Note approximate parallelism of the axes of the drag folds with those of the major folds.

Drag folding (Fig. 112) may be used to determine whether or not a bed is overturned. Similar evidence of shear joints was described in the analysis of shear. On the limbs of folds movement on bedding planes is produced by the squeezing out of the beds in the synclines. While a bed is in its normal position, therefore, the overlying beds move up the dip relative to it. When a bed is overturned, the beds which actually underlie it, but are in reality younger, move up the dip. Due to the rotational nature of the stress which produces them drag folds are unsymmetrical. Their axes are inclined to the bedding, and are rotated from a position normal to it in the direction of movement of the beds on either side of the fold. Hence, if these axes have been rotated into a nearly vertical position, they indicate that the upper bed has moved upward and the beds are in their normal position. If they lie in a more or less nearly horizontal position they indicate the reverse, namely that the beds are overturned. The parallelism of the axes with the axis of the main fold, as well as the direction of movement of the beds, is readily seen from Fig. 112.

The relation between folding and the other kinds of deformation which have just been outlined is of the utmost importance to students who wish to understand and interpret any structure in which folding is involved, and in which the evidence of the position of the folds, of their character, whether normal or overturned, and of the direction and plunge of their axes is obscure. It should be emphasized that minor structures, down to the most minute drag folds, shear planes, and flow structure will be oriented properly in relation to the strain axes indicated by the position of the major fold. In other words, the drag folds are overturned in the direction of movement.

To carry the analysis of the relation between the minor structures and the major folds even farther, some of the following points may be considered. If the strike of the flow cleavage varies from the strike of the bedding, the fold is plunging and the direction of plunge is indicated, for the flow cleavage is parallel to the axis; hence the bed must be converging on the axis, evidence of a plunging fold. If the drag folds plunge the major fold plunges in the same direction. Even if the shear joints on the limbs do not strike parallel to the bedding, the direction and amount of plunge may be determined. It is by the painstaking application of these mechanical principles, through years of patient study, to the limited evidence exposed at the surface, that first Van Hise, and later Leith and his associates, have unravelled the intricate structural problems of the Pre-Cambrian of the Lake Superior Iron Ranges.[1]

The only qualification that the above statements require is that they apply only to the parts of the fold which come under the influence of the external compressive force. As already noted, the beds above the competent bed are folded incompetently, and may be subject to a tension in the direction of the major compression. This may produce thinning over the axis, or tension joints and even normal faulting, but where the external stress is simple compression, such joints and faults will strike parallel or nearly parallel to the axes of the folds.

Where the minor structures found in relation to folds are limited to those described above it is an indication that the system of stresses which caused the deformation is one of simple compression and does not involve rotation in a horizontal plane. Other evidence of such a stress system is found in linear continuity and close spacing of the folds.

Where one segment of the earth's crust is pressed against another in such a way as to form folds, the tendency is for the first fold to develop close to the point of application of the stress, and to extend the full length of the area affected. This tendency may be lessened by variations in the amount of relief afforded at different points, but it contrasts with the tendency of rotational stress to produce short folds, usually with an en echelon or offset arrangement. The Appalachians offer a notable example of very long, continuous folds. Chamberlin has recently brought out other evidence to show that the effects of rotation, if present at all, were slight.[2]

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[1] Van Hise, C. R., Principles of North American Pre-Cambrian Geology. U. S. G. S. *Sixteenth Annual Report*, pp. 573–894, 1894–95.

Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior Region, *Monograph* 52, U. S. G. S., pp. 118–143, 1911.

[2] Chamberlin, R. T., The Strain Ellipsoid and Appalachian Structures, *Jour. Geol.*, vol. XXXVI, pp. 85–90, 1928.

In the preceding pages it was shown that after the inception of deformation in a fold the full intensity of the stress is not transmitted through to the other side, due to its dissipation in the performance of the work of deformation. When the limbs of the fold have been forced together sufficiently, however, the fold acts as a block and the stress is transmitted through it regardless of the bedding. When this occurs the fold is termed *closed*. Under the conditions we have assumed, of deformative stress from one direction only, a second fold is therefore not apt to develop until the first is closed. The first fold may produce initial dips just beyond it, however, which will aid in locating the second fold close to it. This may occur either through movement in the beds themselves, the forcing down of the competent bed in the syncline beyond the fold by weight thrown on the limb of the fold, or by the compression of the mass below the strata and the development of an incompetent fold due to vertical stresses. In any case there is a tendency for the second fold to form close to the first, and this may be said to be characteristic of folds produced by simple compression. It contrasts with the wide and erratic spacing produced by rotational stress. Plate C, Appendix III, illustrates this sequence in the two folds at the right, but it also shows that the competent stratum may transmit the stress some distance beyond the first to form a fold on an initial dip. Cases of this sort are found in the widely spaced folds of the western edge of the Appalachians.[1]

Folding Due to Horizontal Rotational Stress.—In the case of folding produced by a rotational or shearing stress acting in a horizontal plane the relation of the folds to the strain axes, and therefore to the other kinds of deformation, is not the same as in the case of folds due to compression. (See Fig. 113.)

Folds produced by a shearing stress result from the horizontal shortening at 45 degrees to the direction of the forces of the couple. This is the strain axis of shortening. As deformation proceeds this axis is rotated toward a position normal to these forces. The folds will of course form with axes at right angles to this shortening;

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[1] Monterey Folio, Va. and W. Va., U. S. Geol. Atlas, No. 61.

hence they also will lie diagonal to the forces of the couple, the angle being 45 degrees or less. If the deformed area is narrow this produces an en echelon arrangement of the folds.

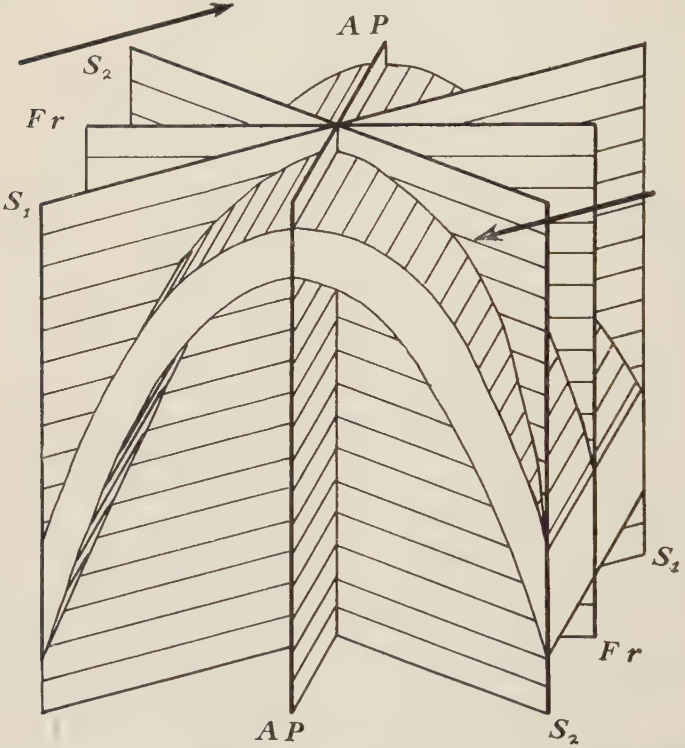


FIG. 113.—A fold developed by a shearing stress in a horizontal plane, showing the position of the shear planes, S_1 and S_2, and the plane of fracture, *Fr*, in relation to the axial plane of the fold, *AP*.

The effect of shear, and therefore the shortening, may be distributed throughout the area undergoing deformation. It will be transmitted to the strata through the underlying basement, and folds may develop at any point where there is an initial dip. The spacing of such folds is therefore a matter of chance. They may be widely or closely spaced, long or short, large or small, depending on the amount of deformation of the basement each fold is required to relieve. This is in contrast to the long regular folds produced by compression.

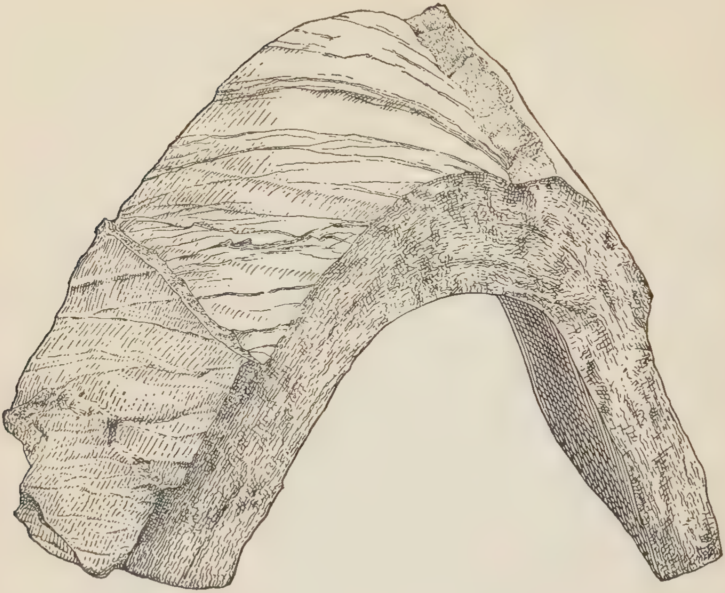
Another effect of the even distribution of the shortening throughout the mass is to give compression, which acts on the folds equally from both directions at the same time. This tends to produce symmetrical folds, other conditions being equal, and if unsymmetrical folds develop, due to conditions of initial dip, their axial planes may be inclined in either direction. This is in contrast to the case of external compression, which tends to form unsymmetrical folds all inclined in the same direction.

In folding, the only possible direction of relief is upward. In shear in a horizontal plane there is horizontal tension at right angles to the direction of shortening, or parallel to the axes of the folds. As folding is incapable of relieving this stress, some other type of deformation may be looked for where such a shear is believed to exist. Either shear or fracture may serve.

The theoretical position of shear planes is parallel to and normal to the forces of the couple. Where the couple lies in a horizontal plane the shear planes will be vertical. They will cut across the folds at approximately 45 degrees to their axes. Such a case is suggested by the specimens shown in Figs. 114 and 115. The twisting of the bed also gives the impression of rotational stress.

Fracture tends to develop at right angles to the tension. In the case considered, therefore, vertical fractures may develop striking at right angles to the axes of the folds. In the case of folds produced by compression it was noted that such fractures, if formed at all, would strike parallel to the folds. The strike of such transverse fractures is usually constant, but they may not be vertical, as the action of gravity may tend to incline them at a gentler dip. If they are sufficiently developed they may become faults, and the displacement on them will be normal.

Within the folds themselves secondary shear, fracture drag folds, and possibly even flowage may develop, but the presence of



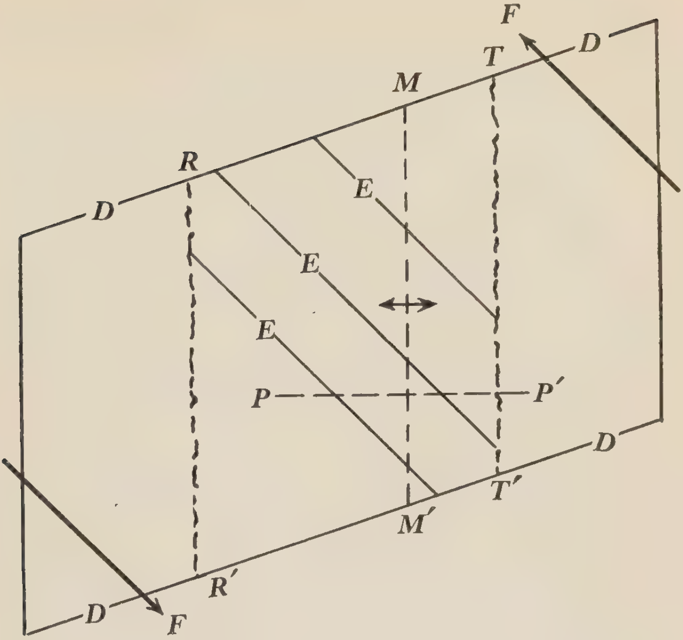
(*a*)

FIG. 114.—Description and interpretation. The diatomaceous shale of the California Miocene is a thin-bedded formation, which is often intimately folded and cross-jointed. The drawing represents such a fold, an anticline about two-thirds natural size. Across the axis run two joint planes which form the front and the back of the specimen. They are cleanly cut off, hence they are probably shear planes. Diagonal to the axis, from left to right in the drawing, extends a series of lines which represent minute fractures. They are not as regular as the first set, but their parallelism still suggests shear joints. The outer strata are also broken parallel to the axis. As seen from above the specimen presents the form of a rhomb, shown in the diagram.

The facts are best interpreted as the effects of shear in a horizontal plane, or a combination of it with compression. The latter is not necessary to explain

diagonal vertical joint systems or transverse fractures is good evidence of horizontal rotational stress.

Folding by Combinations of Stresses.—Any combination of shearing stress and compression will produce effects dependent

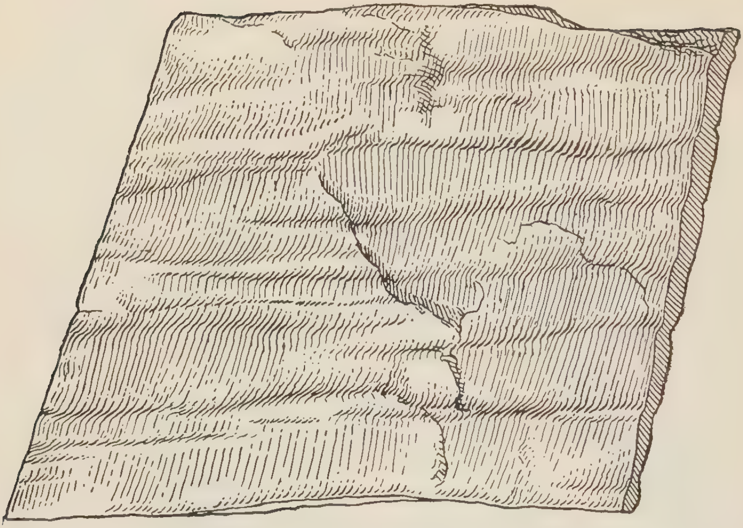


(b)

all the structures shown. The direction of the forces of the shearing couple are shown in the diagram as *FF*. These caused shortening along the strain axis *PP′*, normal to the axis of the fold. This compensated for the compressional component developed by the shear, but not for the tensional component, which acted parallel to the strain axis *MM′*. The elongation in this direction was accommodated by the development of two sets of shear planes *DD′* and *EE′*. The combination of compression with the rotational stress, shown as *C*, would favor the first set, as shown by the specimen. The fractures *RR′* and *TT′* are subordinate effects of the stretching of the beds over the axis of the fold.

on the relative magnitudes of the two. Let us consider some actual cases, and the probable stresses that formed them.

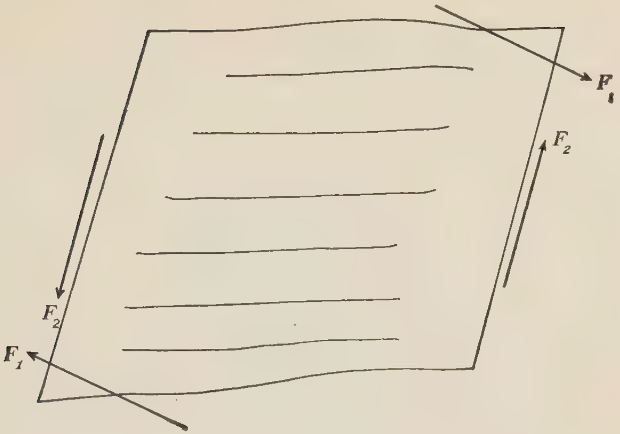
Along any folded mountain chain there are differences in the intensity of the stress or the character of the resistance.



(a)

FIG. 115.—Description and explanation. The drawing represents a specimen of foliated green schist, a metamorphic rock formed from shale, from near Chewelah in the state of Washington. Rocks of similar structure are of common occurrence in districts of moderate metamorphism. The original bedding of the shale was parallel to the plane of the paper. A readiness to cleave along closely spaced lines (flow cleavage) runs from left to right. Smooth joints, spaced at intervals of several inches, cross the other structure. Furthermore, the schist exhibits folding on a small scale, but commensurate with the thickness of the layers, with the axes of the folds running parallel with the closely spaced cleavages.

These differences give rise to curves in the chain, which in turn cause shearing stresses in a horizontal plane. This is particularly true at the ends of the belt of folding. If the whole chain is curved, as in arcuate mountains, the rotational effect will be absent only at the center of the arc. The result of the shear is to produce folds en echelon, which are oriented at slight angle to the trend of the whole range, but which lie more nearly parallel to it than does the local trend. Examples of this sort are found in the Appalachians, as shown in Plate L, Appendix III, and in the



(*b*)

As in the preceding case, Fig. 114, these structures can be explained by a combination of compression and rotational stress, the latter acting in the plane of the specimen. The direction of the forces of two couples which might have produced the deformation is shown, F_1F_1' and F_2F_2'. The angle of the shear planes (bounding joints of the specimen) with the axes of the folds is rather large in the couple F_2F_2'. Normally this would be less than 45 degrees, as the tendency is to rotate the axes of the folds into parallelism with the forces of the couple, hence with the shear plane. Hence we deduce that the couple F_1F_1' caused the deformation, and that it was combined with compression which favored the joints *DD*, rather than the joints which would otherwise have formed parallel to the forces of the couple.

Jura Mountains in Switzerland, shown in Fig. 116. The effect is more pronounced in the latter. Experiments have been conducted by S. Tokuda [1] and T. A. Link [2] to show the development of arcuate mountains and the effects of differential application of stress. Tokuda applies his results to an interpretation of the structure of the Japanese Archipelagoes. Plate K, Appendix III,

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[1] TOKUDA, S., On the Echelon Structure of the Japanese Archipelagoes. *Japanese Journal of Geology and Geography*, vol. V, No. 1–2, 1926–1927, pp. 41–76.

[2] LINK, THEODORE A., En Echelon Folds and Arcuate Mountains, *Jour. Geol.*, vol. XXXVI, pp. 526–538, 1928.

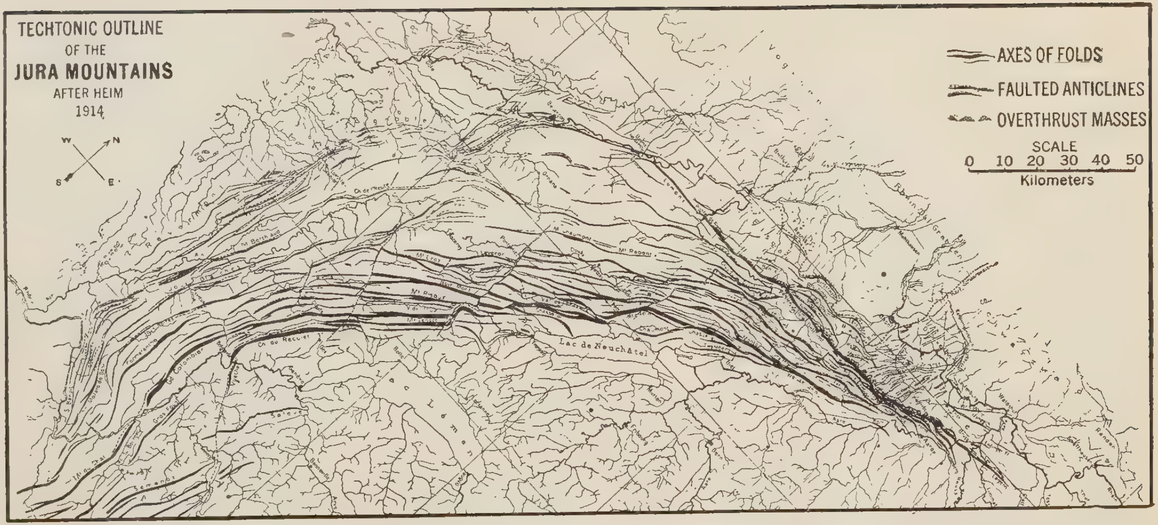

Fig. 116.—The Jura mountains in Switzerland (after Heim). An arcuate system of folded mountains. Note the tendency to form en echelon folds where the arc is most strongly curved, and the transverse shear faults with horizontal displacement in the central portion of the range.

illustrates two of his experiments. Link points out how a variation of competency in the beds along the strike of the folds may develop differential transmission of stress and produce en echelon structures. He applies this to the folding of the Jura.

It is obvious that the more the trend of the zone of en echelon structures varies from the main trend of the range (that is, from a position normal to the deforming stress), the greater will be the effect of horizontal shear and the less the effect of compression. The resulting secondary structures of shear and faulting will increase at the expense of the folding. Under analysis of faulting an example is considered in which the trend of the en echelon structure is at right angles to the compression. (Page 286.) In this case folding is due only to the shortening effect produced by the shear itself, and is practically negligible.

Further consideration of Plate L, Appendix III, showing the Appalachian chain, gives us additional evidence of the direction from which the compression came. The folding is obviously much more intense in the sections of the line which are concave to the southeast. The deformation is naturally more intense where the deforming block has moved farthest. Hence the source of the pressure must have been from the southeast, otherwise the deforming block would have travelled farthest where the deformation was least.

The cases considered above are those in which folding is the dominant form of deformation. In the Coast Ranges of California the great faults control the structure, and the folding is secondary, rarely extending beyond the limits of individual blocks. The dominant effect is one of shear in a horizontal plane, the mass beneath the ocean moving northwest relative to the continent. Compression is effective enough to produce closed and overturned folds, and to prevent the development of structures due to tension. The character of the folds is shown in Fig. 117, illustrating the oil-bearing structures of the Los Angeles Basin. The individual folds may be quite long, but they are not uniformly developed throughout their length. Shear is not distributed uniformly through the mass, but is localized along the faults. Where the

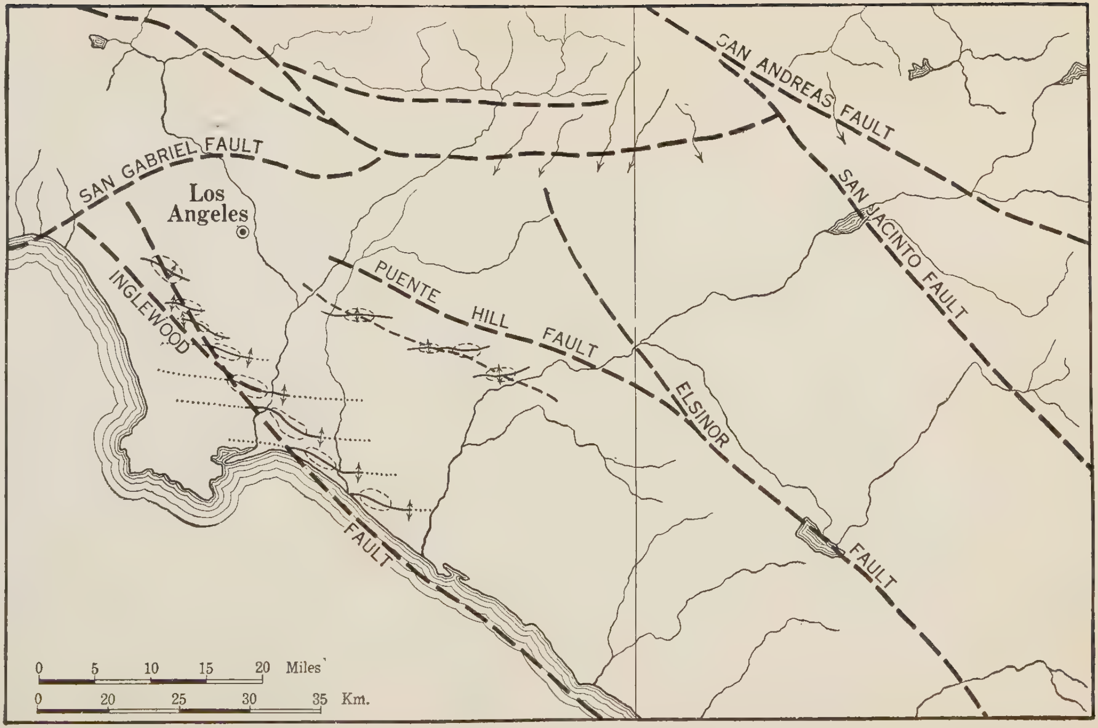

FIG. 117.—The faults and folds of the Los Angeles basin, California. The oval areas indicate doming of the folds which has permitted the accumulation of oil. Note the en echelon arrangement of these areas and their coincidence with the lines of faulting.

lines of folding cross the faults folding is intensified and domes are produced in which the oil has accumulated. The folds lie at an angle to the faults, and the domes along the faults are therefore en echelon.

In Wyoming many of the structures appear to have been formed by stresses in which horizontal shear was involved. There are no great shear faults through this region, but the folds lie en echelon and are characterized by a large number of domes or "closed structures." Transverse normal faults [1] are characteristic of most of them. In some places these may be explained by tension along the axis due to the doming of the fold, but in others the faulting is so pronounced that it must be attributed to the action of external forces, presumably horizontal shear causing tension along the axis of elongation.

Development of Anticlinoria and Synclinoria.—Composite folds, those structures made up of folds of more than one magnitude, have been touched on already in the discussion of drag folds. The scale on which they may develop, however, ranges from microscopic drag folds on very small major folds to competent folds formed by compression in a sinking geosyncline or larger competent fold.

Both synclinoria and anticlinoria may be formed by the effects of drag. The chief characteristic of such structures is the parallelism of the axes of the major and minor folds, already emphasized as of great value in their interpretation.

Another typical development of composite folds is in the troughs of synclines and under the crests of competent anticlines. Here the structures may not approximate so closely the ideal conditions. The axes are apt to incline toward the major axis in the anticlines and away from it in the synclines. Fine examples of synclinoria formed in this way are the Anthracite Basins of Pennsylvania and the synclinorium of the Ouachita uplift. The former have been described in great detail by the geological surveys of Pennsylvania. The latter is illustrated in the Hot Springs Folio,

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[1] Estabrook, E. L., Faulting in the Wyoming Oil Fields, *Bull.*, Amer. Assoc. Pet. Geol., vol. 7, pp. 95–102, 1923.

No. 215, of the U. S. Geological Survey. In both cases the folded series consists of a competent bed which underlies a great thickness of incompetent beds. The latter are forced together and crumpled in the synclines between the competent anticlines rising on either side of them. We may extend this comparison and say that all composite folds are the result of variations in the competency of the beds in a series.

Depth of Deformation in Relation to Folding.—The intensity of folding, combined with the amount of uplift which accompanies it, may be used to determine the depth of the mass which suffered deformation. R. T. Chamberlin has outlined the procedure, and has applied it to two specific cases.[1] He distinguishes from his results two types of mountains, a " thin-shelled " type and a " thick-shelled " type. In the Appalachians the shallowest depth indicated in the section measured by him is 5.7 miles and the maximum depth is 32 miles. In the Rockies the deformation is shown to extend to a depth of 107 miles. In the former case a thin shell has been closely compressed, in the latter a thicker zone has been less strongly compressed, but the deformation has resulted in greater uplift.

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[1] Chamberlin, R. T., Appalachian Folds of Central Pennsylvania, *Jour. Geol.*, vol. XVIII, pp. 228–251, 1910.

Chamberlin, R. T., The Building of the Colorado Rockies, *Jour. Geol.*, vol. XXVII, pp. 145–164, 225–251, 1919.

CHAPTER XII

ANALYSIS OF FAULTING

Faulting necessitates shearing stress. Four types distinguished according to orientation of this stress. Faulting due to tension and gravity: the Balcones and Mexia fault zones, en echelon normal faults. Faults of dominantly vertical displacement: orientation of fault plane, upthrusts. Overthrusts and underthrusts: factors determining their relative importance and criteria for distinguishing between them. Highland structure. Faults due to horizontal rotational stress; the faults of the California Coast Ranges.

Faulting by definition requires displacement parallel to a plane of parting. Hence it can only be produced where shearing stress is present. Conversely, wherever shearing stresses are active and deformation occurs, faults may develop.

Stress within the earth may act in a great variety of combinations. Shearing stresses may be set up in horizontal planes, in any direction in vertical planes or in combinations of the two. Faults, therefore, may assume many different positions and have displacements in any direction.

We distinguish four primary kinds of faults which have their origin in the simpler stress systems. These are: (1) faults produced by tension and gravity alone, (2) faults produced by differential uplift, (3) overthrusts and underthrusts due to horizontal compression, and (4) strike-slips produced by shearing stress acting in a horizontal plane. This classification does not include all possible combinations of the four primary types, of which a great variety occurs. Overthrusts, for instance, may exhibit horizontal displacement parallel to the strike as well as up the dip, and minor thrusts may develop diagonally in the front of an overthrust mass.

Or an upthrust may exhibit combined vertical, inclined, and horizontal movements, giving a curved twist to the movement. The Sawatch fault in the Ten Mile district is of the latter type.[1] But though the complexities of faulting are innumerable an analysis of the four primary types is sufficient for an understanding of the mechanics.

Tension and Gravity Faults.—Where tension is found in the earth's crust it is most effective as a pull in a horizontal direction since gravity opposes vertical extension. The stress system produced by the two forces is one of horizontal tension and vertical compression. The tension may open cracks which are vertical if the rock is strong enough to support itself. If the cracks extend deep enough into the earth gravity acts to produce shearing planes at 45 degrees to the horizontal (Fig. 118) and the masses on either side of the fracture will slide into it on these planes. Normal faults are thus produced. They strike at right angles to the direc-

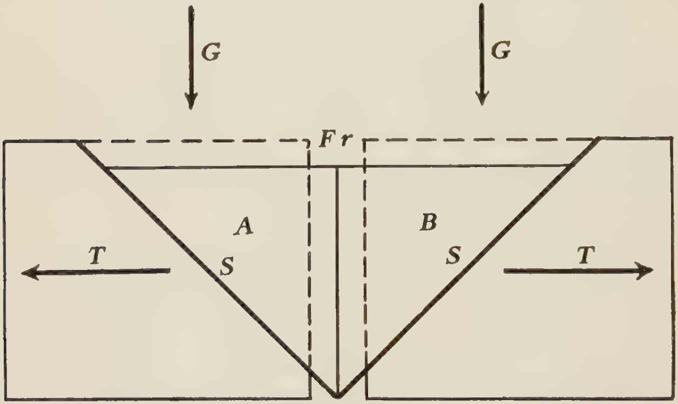

FIG. 118.—Normal faults produced by tension and gravity. The tension *TT* opened the fracture *Fr*. Gravity, *GG*, caused the development of the shear planes *SS*, on which blocks *A* and *B* slid into the space caused by fracturing.

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[1] Ten Mile Folio, Geol. Atlas of the United States, Folio No. 48.

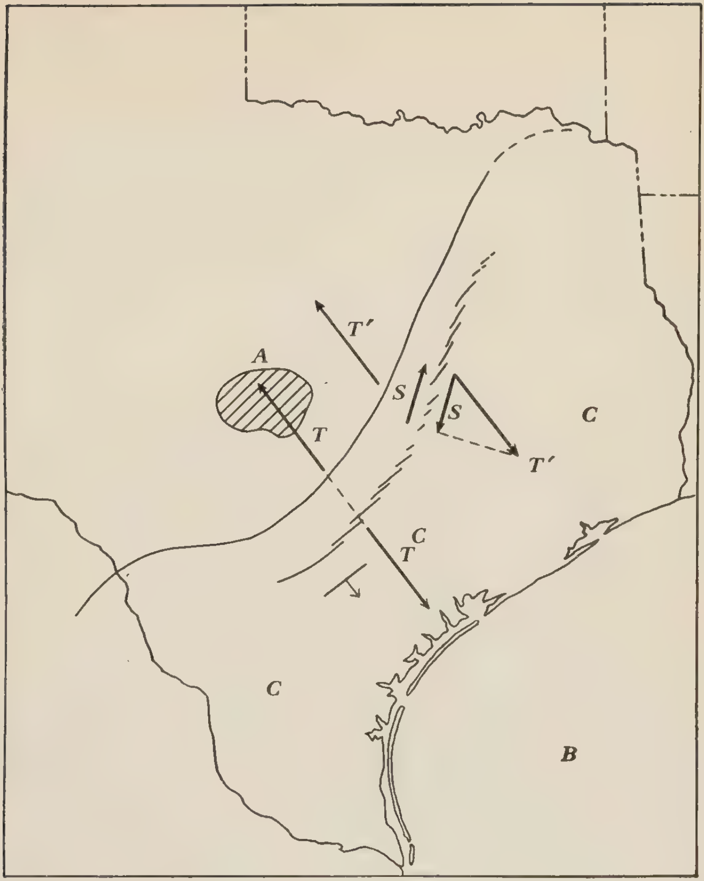

FIG. 119.—The Balcones and Mexia fault zones of Texas. The Balcones fault lies northwest of the Mexia zone, which lies en echelon as shown. The faults are generalized.

The two zones combined form a true Graben, the faults being normal with flat dips, and the displacement being down between the two zones. They are explained by the relative movements of the positive area *A*, the central Mineral Region of the State, and the negative area *B*, the Sigsbee deep in the Gulf of Mexico. The former has been slightly elevated, the latter has been greatly depressed. The result is the tilting of the Coastal Plain *CCC*, as shown, producing tension around the edge of the positive mass *A*. This tension is shown as *TT* and *T′T′*. As the major direction of movement was parallel to the Gulf Coast, shearing components *SS* were set up by *T′T′* which caused the en echelon arrangement of the faults of the Mexia zone. The position of these was determined by the flexure between *A* and *C*, rather than by the direction of tension.

tion of tension, and dip at rather low angles compared to most normal faults.

A fine example of this type of faulting is found in the Balcones and Mexia fault systems of Texas, illustrated in Fig. 119. Foley [1] has shown that the sinking of the Gulf of Mexico, or the relative uplift of the Llano-Burnett region, would produce tension along the flexure between the flat surface of the latter and the plane of inclination toward the former. This flexure would lie in an arc around the elevated area, which is the position of the fault zones.

In cross-section the zones of two sets of normal faults (the Balcones on the northwest, the Mexia on the southeast) would dip toward one another. Oil field development has shown that the dip of the fault planes varies from 40 to 60 degrees. This is very low for normal faults. If the beds are projected across the fault zone they show little vertical displacement other than that due to the original tilting. The zone is therefore a true Graben. The only forces necessary to produce it are tension and gravity.

The Mexia zone shows an interesting effect produced by the localization of the fracture at an angle to the direction of tension. The faults of this zone lie en echelon, the northern end of each fault passing east of the south end of the fault beyond it. This indicates differential movement parallel to the strike of the zone. The southeast side has moved south relative to the northwest side. If the zone as a whole is considered, uniform movement toward the Gulf of Mexico would produce this effect. The en echelon arrangement begins where the curve of the fault line to the north diverges from the line of the Gulf Coast.

An important result of this lateral displacement is the arching of the strata in gentle flexures with axes at right angles to the faults. This is produced by the compression along the strain axis of shortening resulting from the horizontal shearing stress. It is of great economic importance, as it forms the closure on the ends of the faults which permits accumulation of oil. Drag on the faults produces flexures parallel to the faults, but they are not directly related to the regional stresses.

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[1] Foley, Lyndon L., Mechanics of the Balcones and Mexia Faulting, A.A.P.G. *Bulletin*, vol. 10, 1261–69, 1926.

The foregoing example of faults produced by tension is one where the structures formed are of regional magnitude. A much more common case is that where the tension is local, due either to torsion or to shear in a horizontal plane. The en echelon faults of north central Oklahoma have been much discussed. They are normal faults in which the displacement is apparently due entirely to the effect of gravity. They lie in belts trending north and south and they strike approximately northwest. They have been attributed to shear in the sediments produced by horizontal displacement on faults in the granite below and to combinations of torsion and tension due to differential uplift. R. E. Sherrill [1] attributes them to torsion produced by relative depression of the northeast and southwest corners of the area, causing tension in a northeast and southwest direction. This tension is localized along slight anticlinal flexures (lines of steepening in the westward regional dip) which trend north and south and form the fault zones.

Rollin T. Chamberlin [2] has described another set of en echelon faults in the Rocky Mountain region. The belt is several times as long as it is wide, and the faults strike at approximately 45 degrees to its trend. This line runs east and west and is apparently produced by differential horizontal displacement of two sections of the Rocky Mountain thrust, one of which has pushed farther into the Plains region than the other. Torsion may have contributed to the effect.

Faults of Dominantly Vertical Displacement.—Faults on which there is evidence of relative vertical displacement of the two blocks, but where there is no evidence of local tension or compression, may be attributed to shear in which the forces of the couple are vertical. The movement may be either the elevation of one block or the depression of the other or both. If the first can be demonstrated the fault is called an upthrust. It may be shown by such evidence as the raising of marine sediments above sea level or the rejuvenation of erosion on a topographic surface. Evidence of the latter may be found in the depressing of the topographic surface below sea level or in sedimentation in an area previously subjected to erosion.

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[1] SHERRILL, R. E., Origin of the en Echelon Faults in North Central Oklahoma, A. A. P. G. *Bulletin*, vol. 13, p. 31, 1929.

[2] CHAMBERLIN, ROLLIN T., A Peculiar Belt of Oblique Faulting, *Jour. of Geology*, vol. XXVII, pp. 602–613.

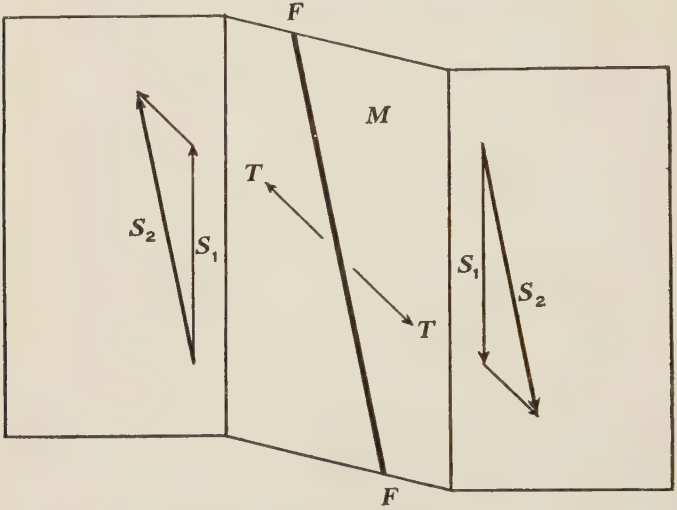

FIG. 120.—Orientation of a fault plane due to vertical shearing stress. The initial shearing stress is shown as S_1S_1. As it increases it causes elastic strain shown by the distortion of the mass *M* from a horizontal position. The difference between S_1S_1 and S_2S_2 is the difference necessary to cause this distortion. The distortion develops tension at 45 degrees to the direction of shear, shown as *TT*. This is a component of the final shearing stress S_2S_2, and deflects it from the vertical. The fault plane finally caused by the increase in the shearing stress beyond the strength of the rocks is parallel to the final stresses, hence it is oriented as *FF*, and the fault has the appearance of a normal fault, though there has been no horizontal extension of the mass.

These effects may be attributed to other causes, and many other types of evidence may be brought to bear upon the actual displacement of the blocks. We are concerned however only with the relative displacement and the angle assumed by the fault plane.

Figure 120 shows the distortion of a mass by a shearing stress within the elastic limit and its effect upon the position of the shear plane which will develop as the stresses become sufficient to cause failure. The tension produced along the axis of elongation tends to deflect the forces of the external couple and to rotate the plane of shear backward against the direction of rotation of the original couple. Applying this to the case of an upthrust fault the tendency will be to form a shear plane which hades to the downthrow. In other words, a normal fault will be produced, other conditions being equal. Thus a normal fault does not necessarily imply tension in a horizontal direction. The strain before failure in the theoretical case is equivalent to the drag which is so common on faults. The apparent lengthening of the mass due to the inclination of the fault in reality only compensates for the shortening produced by the drag.

Overthrusts and Underthrusts.—The position of shear planes due to horizontal compression has already been touched on in the analysis of folding, page 267. They strike at right angles to the stress, and dip in either direction at angles of 45 degrees. Such shear planes may develop in any rock mass; in fact they are the usual type of structure found in massive rocks; but they develop in sedimentary rocks only when these are too thickly bedded or too thinly bedded to fold. Displacement on them is at first slight, but with the continuance of deformation the displacements become greater and the effect is to locate them first on one set of shear planes and second on individual planes in that set.

Normally the set of shear planes which dips toward the direction of stress affords the easiest relief of strain. Overthrusts therefore are more common than underthrusts, unless there is some external factor which favors the planes which dip away from the source of pressure. Differences in weight, friction, immobility, or other sources of resistances offered to advance in any direction may determine whether an overthrust or an underthrust shall develop. When a mass is thrust against another which rises above it, a couple is produced which tends to favor the planes dipping away from the force and which therefore promotes underthrusting. If we infer from the visible structures that the great mountain ranges of South

America and Japan are formed by pressure originating in the oceanic deeps adjacent to them, we have such a condition, and it is likely that great underthrusts form the marginal structural features of these regions. A series of thrusts lies along the southern edge of the Himalaya Mountains and dips back under them. The interpretation of these as underthrusts or overthrusts depends upon the theory of diastrophism which one accepts. If it is assumed that the continental masses are expanding and that the source of pressure is under the plateaus of Tibet, these faults are overthrusts. If the deforming force is thought to have originated in the ocean basins they are underthrusts.

The distinction between overthrusts and underthrusts can sometimes be made on the ground of intensity of deformation. It was shown in the analysis of folding that folds will be more closely compressed on the side toward the source of pressure. In the front range of the northern Rockies great thrust planes are found [1] on which pre-Cambrian and Paleozoic rocks have overridden Cretaceous and Tertiary sediments from the west. The latter are folded, apparently by the force transmitted in the overthrust itself, or by the drag on its under side. The folds die out eastward. As the area west of them is intensely deformed, the logical inference is that the pressure was from the west. Hence the faults are overthrusts.

In the Mount Diablo region [2] east of San Francisco Bay in the California Coast Ranges, a thrust fault occurs which dips to the east under the San Joaquin Valley. Folding of the beds above the thrust planes appears to die out eastward. The region to the west is intensely deformed. It may therefore be interpreted as an underthrust. In using varying intensity of deformation to determine the character of faults the factor of localization of this deformation in zones of weakness should be carefully considered. For instance, a series of folds in sedimentary beds may reveal to the casual observer more proof of deformation than a sheared mass of igneous or metamorphic rocks adjacent to it.

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[1] Willis, Bailey, Stratigraphy and Structure of the Lewis and Livingston Ranges, Montana, *Bull.* G. S. A., vol. 13, pp. 305–352, 1902.

Blackwelder, E., Geology of the Wasatch Mountains, Utah, *Bull.* G. S. A., vol. 21, pp. 517–542, 1910.

Richards, R. W., and Mansfield, G. R., The Bannock Overthrust, Idaho, *Jour. Geol.*, vol. 20, pp. 681–709, 1912.

Ziegler, V., Foothills Structure in the Rocky Mountains, *Jour. Geol.*, vol. ~~26~~ 25, pp. 715–740, 1917.

Dake, C. L., The Hart Mountain Overthrust, Wyoming, *Jour Geol.*, vol. 26, pp. 45–55, 1918.

[2] Clark, Bruce L., Studies in the Tectonics of the Coast Range of California, *Bull.* G. S. A., vol. 28, 1927, p. 163 (abstract).

Low-angle Thrusts.—The problem of low-angle thrusts is one of the most interesting and baffling of the mechanical problems of structural geology. It is obvious that such thrusts are formed by horizontal compression. Such a force would normally form shear planes with dips of 45 degrees or more. The great thrust planes of the Scottish highlands, of the southern Appalachians region, of the Carpathians, the Alps, the Rockies, and many other regions dip at very much lower angles. Many of the faults mentioned are not controlled by folding as they are formed in massive igneous and metamorphic rocks. What is capable of producing shear on these nearly horizontal planes and of causing displacements on them of many miles? Rollin Chamberlin and W. Z. Miller[1] have summarized the factors which tend to lower their angle of dip as follows:

> 1. The normal or direct stress which acts along planes inclined 45 degrees to the line of application of force, has an intensity as great as that of the tangential stress. It acts as a frictional resistance to shearing by the tangential stress. The lower the angle of the fracture plane, the less will be the frictional resistance due to the normal component of stress. Hence the tendency to fracture at angles below 45 degrees.
>
> 2. Rotational strain, which will lower one of the planes of no distortion (shearing planes) from 45 degrees in pure nonrotational strain to 0 degree in the extreme case of rotational strain. Rotational strains may be developed from horizontal component stresses: (*a*) in homogeneous material: (1) by any factors which will increase the intensity of the tangential stress in the upper portion of the mass undergoing thrusting with respect to that in the lower portion; (2) by any factors which will

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[1] Chamberlin, Rollin, and Miller, W. Z., *Jour. of Geol.*, vol. XXVI, pp. 1–44, 1918.

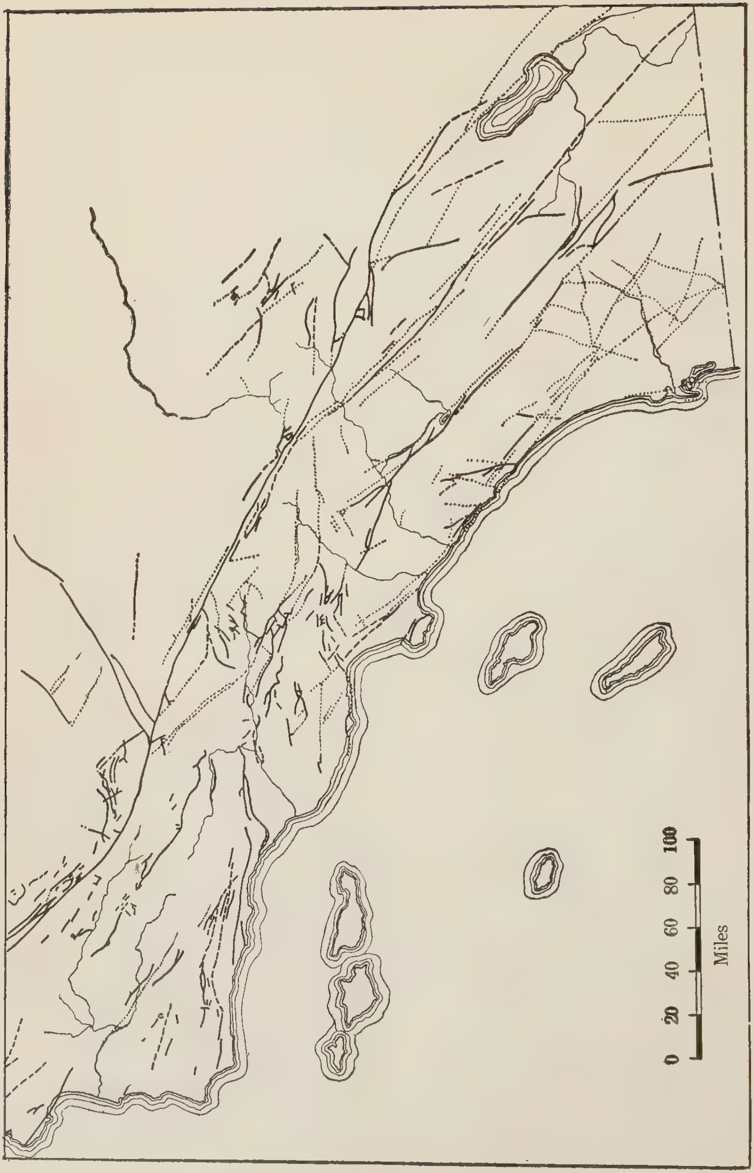

FIG. 121.—Fault system of Southern California.

lessen the resistance in the surficial portion without changing that below; and (3) by any factors which will increase the resistance, of the deeper portion of the zone subjected to thrusting while the upper portion remains freer to yield; (*b*) in heterogeneous material by bedding or similar structures, which present differences in competency of the right sort and thus call into operation some of the foregoing factors.

3. Preliminary piling up of material in the first stages of deformation, thus increasing the load and the vertically acting gravitative force. The combination of the horizontal thrusting and the vertical gravitational force gives a resultant which is inclined downward from the horizontal. Even should faulting take place in a plane 45 degrees from this resultant, it would still be inclined less than 45 degrees from the horizontal.

4. Possible minor factors, as heterogeneity of material, length of deformed mass with respect to its other dimensions (after analogy of long column), shape of deformed mass, etc.

Highland Structure.—The mechanics of the faulting of the Scottish highlands, described on page 107, Figs. 61–62, is explained by the application of the foregoing principles. Shear planes seem to have formed first at comparatively steep angles. These piled up one above the other until the gravity component of stress deflected the resultant between it and the compressive stress downward, and a nearly horizontal shear plane was formed beneath the whole mass, which then rode forward on it. Another interpretation of the minor shears is that given for the shear joints on the limbs of a fold. (Page 232.) They occupy the correct position for shears developed by the combined effect of gravitational compression and shearing stress induced by movement on the major fault. In the first explanation the minor faults form first. In the second the major faults form first. Probably both cases are to be found in the Scottish highlands.

Strike-slip Faults Due to Shear in a Horizontal Plane.—Mention has already been made (page 279) of the great fault system of the Coast Ranges of California. This system comprises a few faults of great magnitude and a very large number of minor faults. In southern California there are four major faults (Fig. 121) which are very straight, are evenly spaced about 25 miles apart, and run parallel for a distance of about 150 miles. They are apparently high-angle faults. They thus display the characteristics to be expected of shear planes developed by rotational stress acting in a horizontal plane. Similar faults extend northward throughout the Coast Ranges, though with less regularity.

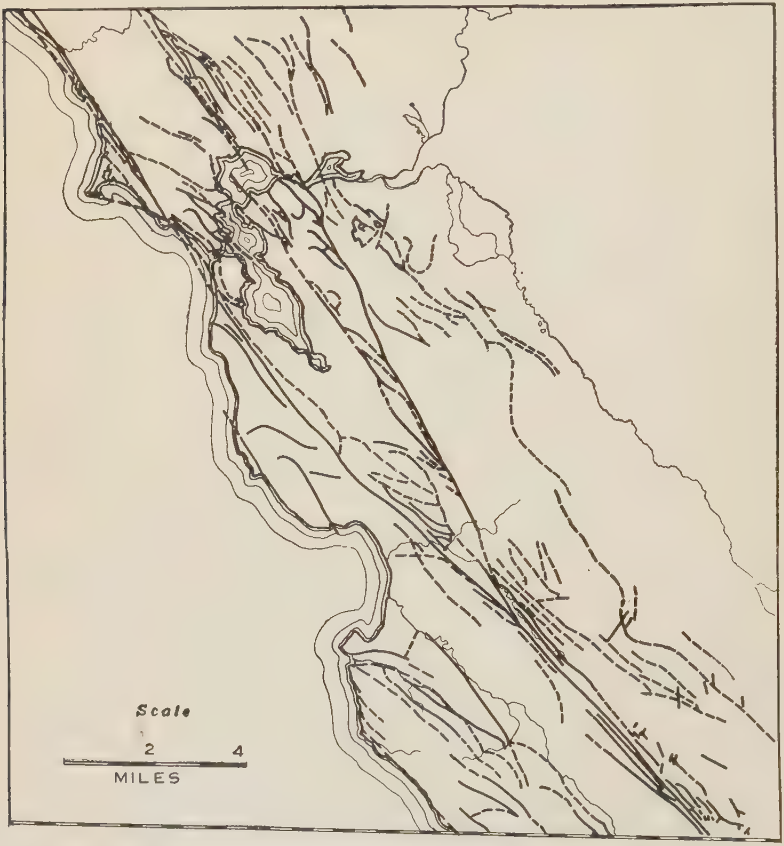

FIG. 122.—Fault system of the Coast Ranges of Central California.

The basement complex consists of metamorphic schists and batholiths which are penetrated by basic intrusives. The structural rigidity of the complex is such that folding is impossible; hence the general predominance of shearing is to be expected. Folds occur in the sedimentary formations but they are usually confined to a single fault block, sometimes of moderate size. Adjacent fault blocks frequently differ radically in the nature and degree of folding exhibited by the sediments.

The superficial structures thus display the character of deformation in the underlying mosaic. The shearing in the basement complex has been repeatedly renewed and has extended up through Cretaceous, Tertiary, and Pleistocene strata. The blocks cut out by faulting have been pressed together and great vertical displacements have occurred, but the dominant displacement has been horizontal.

The movement on these faults is in general to the northwest on the southwest side. The actual displacement on the San Andreas fault observed at the time of the San Francisco earthquake in 1906 was in this direction, and in the Carrizo Plains drainage lines and other topographic features have been offset in comparatively recent times in the same sense. Though no specific statement can be made for the Coast Ranges as a whole, in many parts the evidence of the compression structures is to the same effect. The faults trend approximately northwest, while the compression features either parallel them or trend more nearly east and west.

The structure of the Coast Ranges as a whole is extremely complex. In the topographic trends and distinct earthquake districts there is evidence that several separate sources of compression or rotation exist, which act independently. However, a general suggestion regarding the origin of the major faults may be found in the apparent direction of the deformative force and the position of the continental mass. A force directed from the south-southwest impinging on the continent at an angle approaching 45 degrees would produce a rotational stress in a horizontal plane, which would account for the development and direction of movement on these faults.

Since they are active these faults are expressed in the topography by differential movement rather than by differential erosion. A study of the physiography of the Coast Ranges is therefore of value in determining which faults are vigorously active in contrast to those which are relatively quiet.[1]

Other faults which show considerable horizontal displacement have been described in various regions. The transverse faults in the Jura Mountains shown in Fig. 116 are vertical shear planes produced by the compression which formed the folds. Lateral relief along the axes was afforded by the tension induced by the longitudinal stretching of the belt of folding around the buttress of the Alps as they were forced into it.

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[1] Willis, Robin, Physiography of the California Coast Ranges, G. S. A. *Bulletin*, vol. 36, pp. 641–678, 1925.

SECTION III

METHODS OF ATTACK

CHAPTER XIII

FIELD METHODS

How to think in the field. Intellectual personality; breadth or specialization; engineering vision. Equipment; as little as will serve. Note-taking, an art to be acquired; requirements and limitations; structure and architecture; measurement, surveying, and mapping. Physiographic questions; what streams tell; live regions and dead ones; physiographic clues. Surveying for geology; reconnoissance methods; pacing, time traversing; sighting; plotting angles; objects of survey; reconnoissance; key studies. The explorer versus the specialist. General surveys for geology; a day's work; some useful criteria. What does the landscape say? Stratigraphy; observations on strata; their significance. Structural problems. Special surveys. Conclusion; the method of multiple hypotheses.

Methods of geologic field work are individual. No two geologists work alike because geologic field work is thinking and no two men think alike. It is important to emphasize the thinking. Geologists enjoy their outdoor life, the freedom of the nomad, the delights of the artist, the inspiration of the poet, the aspiration of the seer, according to their gifts. But the geologist who would understand must think, think intensively, earnestly, and truthfully. His thinking is the soul of his work and his habit of thinking fixes his methods.

The practice of observing is very unequally developed, according to capacity and training. My friend hears ten birds singing where I hear none. I see the color, form, and texture of the stone he stumbles over. Not that I am deaf nor he blind, but our receiving sets are differently pitched. And as we differ in the kind of thing we observe, so do we differ also in the capacity to link our observations into a chain of thought.

Walcott, as it happened, was once out for trilobites in the quartzites of the Blue Ridge in Virginia. Many good fossil hunters had looked for them there in vain. We broke the ringing rock, where it is exposed in the gorge of the James River, for hours, but found nothing. The rock broke across the fossils, if there were any, and they were too thin to be seen. The next morning we looked across the Valley of Virginia to the Blue Ridge, 4 miles away, and could trace the low ridge formed by the quartzite along its face. Walcott called my attention to the ravine of a small stream, which crossed it, breaking the even ridge crest by a gap which lacked the sharp features of the river gorge. "The trilobites are waiting for us there," said Walcott. "They have been waiting a long time. Let's go." And there we found them in abundance in the weathered rock shown by the gap, which split parallel to the bedding planes on which the trilobites had died.

It was not luck. It was method. The method of reasoning from the conditions of failure to those of success, the method which in its broader application consists in reasoning from correct observation to related inference; in testing inference by directed observation and passing to further inference; and so by alternate observation and inference arriving at a conclusion based on sound interpretation of facts.

That is the method of geologic thinking—a strenuous, exacting method, which requires the constant exercise of the best powers a man possesses, backed by sound training. Naturally, the ability to apply it grows with experience.

In offering the following outline of field methods, I would point out that they are individual, in that they are those which I find useful, and they are restricted in scope to the purposes of geologic field work in relation to structural geology.

PERSONAL QUALIFICATIONS

The physical, mental, and moral qualities of a first-rate geologist must be of a high order, whether he follows the more scientific or the more practical branch of the profession. But taking these for granted, there is a distinction between two types of mind which determines what a particular investigator can do well. It is the distinction between the explorer of continents and the student of crystals, between the extensive and intensive application of thought. Many of the older geologists were explorers, not only in the sense that they travelled widely in little known lands, but also in that they reasoned widely on little known subjects. They were broad men, who grasped strongly the whole scope of earth science, and developed their speculations with corresponding daring. As our knowledge of earth processes and history has grown beyond the capacity of any one mind, the special student has increased in numbers and his individual labors are directed toward narrower fields. But the explorer and the specialist are both necessary to the progress of the science, and neither can do the other's work satisfactorily.

The broad class to which any would-be geologist belongs is usually apparent by the time he graduates from college; it is often indicated earlier in his career by the studies he prefers, by his grasp of the larger or more detailed aspects of his problems, and by the lifting power of his imagination. His studies should be directed accordingly, either to ground him in the fundamental principles of geology and its allied sciences in general, while teaching thoroughness in key-studies, or to guide him step by step to that intimate understanding of the more limited range of fact and theory essential to success in the specialty in which he does well. Specialization, however, should be deferred as long as possible in a man's studies, in order that he may spread his roots widely. Otherwise, he is apt, like one of those Japanese cypresses whose roots have been stunted for centuries, to remain very small, even though he grows in years.

For the best understanding of structural geology, general ability should be accompanied by the capacity to see things in three dimensions, the ability to see through a solid body and recognize the form of its further side or the details of its internal structure. This is a qualification for mechanical engineering, but in geology the dimensions of the masses, whose positions in space and relations to one another must be grasped, are so great that the mind of a geo-mechanic is required. As, in comparison with geologic eras, the ages of human history shrink to seconds, so do the magnitudes of geologic structures dwarf human measures of length and mass. The uplift of the Himalayas from beneath the seas to the towering height of Everest is an effect which we can measure, it is true, but which is incomprehensible in our terms of inertia, force, and time. Yet the structural geologist should be able to understand the mechanics of that movement by application of principles which are worked out in the laboratory. To do so he must be able to see that mountain range in his mind's eye, to see through it, to see under it, and to realize how the forces are at work around it and in it.

EQUIPMENT

Assuming that a man has the physical and intellectual equipment necessary to the practice of structural geology, his accessory instruments are very simple. Notebook and pencil, compass and hammer, are the two pairs of essentials. Other instruments are of service in special cases, but any that is not needed should be left behind because it wastes both time and attention.

One of the first problems of field work is to get the desired result without instruments. This requires that a man shall have developed the use of his own faculties in certain special applications to his purpose. He walks from one observation to another and wishes to know the distance—he paces it. He ascends a hill and wishes to know its height—he steps it up by looking on a level with the eye and noting how many times the known height of the eye above the ground goes into the altitude of the hill. He wishes to draw an angle across the coordinates of the notebook page—he plots it by estimate, using the tangents of certain known angles and estimating between them. The methods of doing these things on the scale demanded by geologic surveying and within its permissible limits of error are detailed in subsequent paragraphs, but the purpose here is to call attention to the fact that they can be done without the bothersome tape, the misleading aneroid, or the unnecessary protractor.

Surveying for general geologic purposes should not be compared with that of the mining or civil engineer. Both the latter require great accuracy. But the geologist seeks to fix the dimensions and relations of masses of rock which have, as a rule, somewhat indefinite forms and outlines. He proposes to draw them on a relatively small scale. He is obliged to exterpolate beyond his measured data to a degree that makes the attainment of civil-engineering precision impossible. In general, therefore, it is true that proximate measures suffice, especially when they are checked against more accurate surveys or maps.

A geologist's notebook is something to be chosen according to his personal convenience, unless it be one of a series, in which case it should conform to the adopted style. The common surveying books are, as a rule, not well suited in form or in ruling. A preferred form is about 5 by 7 inches with thirty to fifty pages of strong, stiff paper, surfaced to take and hold pencil well, ruled on one side only in squares of five to the inch, and bound between stiff boards. The ruling should appear on the right-hand page for writing notes or plotting surveys, while the left remains blank for sketches. It is a good plan to have the leaves punched to take out and to file in a loose-leaf binder, so that the danger of loss may be minimized and different classes of notes may be filed in appropriate context.

The pencil should be as hard as HHHH, which makes a sufficiently readable mark, but retains its point and does not rub. It should be sharp and should be kept sharp.

The most convenient and adequate scale, both for ruling and measuring, is a strip torn off of one of the back pages of the notebook and folded lengthwise parallel to the ruling. The fold in hard paper, creased on the flat surface of the notebook cover, is straight, and the ruling gives a scale that is identical with that of the page. The strip serves for temporary memoranda, the inside of it is a good place to sharpen the pencil, and if it blows away another can be had.

The pencil and scale may be conveniently carried in the notebook, under a rubber band, which is necessary anyway to keep the leaves from fluttering. With this equipment and arrangement no time is lost fishing in pockets.

The compasses most in use are the Brunton and the Gurley. The former is in more general use because it shuts up in a compact form, fits the pocket, and can be used for a greater variety of observations. The latter has the advantage of an open face, simplicity, and adaptability to the particular observations which a geologist most often makes. The essential elements of a good compass are a long, steady needle (not too wobbly), a distinct graduation, a clinometer, two levels, and a long straight side parallel with the north-south line. It is conveniently carried in a leather case on the front of the belt, where it may be slipped in and out readily and may serve as a rest for the arm in writing notes.

The hammer should be adapted to its purpose—chipping rocks for casual inspection, breaking out specimens, digging for fossils, trimming specimens—and should suit the convenience of its owner in weight, form, and length of handle. A first-class hammer which suits the taste, that is, expresses the character of its owner, can be obtained only by having it made to design. It should be of drill steel, tempered for rock, and deep enough through the head so that the handle will not work loose with prying. It is a good plan to wrap the handle with tiretape and wind it with cord for a grip. The handle should be a definite length for measuring; 18 inches with a hammer weighing 1½ pounds is a good combination for all around work.

Accessory instruments, which are occasionally useful, are the hand level, the Abney level for slope measurements, the aneroid, and the traverse plane table. They are sometimes required because of the peculiar conditions of the work, but quite as often they are used because the observer is not trained to get results without them.

NOTE TAKING

The art of taking good notes, like the art of writing well, is difficult. The essential requirement is that the observed facts shall be stated adequately and without ambiguity. That which is adequate, I do not say full or complete, depends upon what is necessary to recall to the mind of the geologist all the facts of his observation which he would not otherwise remember when he comes to work up his notes. Facts come first. There are obvious facts, less obvious, and obscure facts. There are facts obviously important in relation to the immediate object of the survey and facts supposedly incidental thereto. There are facts understood and others which are not. Location, form, attitude, color, texture, kind, peculiarities, structure, classification, these and many more groups of facts may enter into the description of an outcrop, but as a rule we select that which seems at the moment significant and let the rest go unrecorded, if not unobserved.

It is therefore very advantageous to have in advance a clear idea of the class of facts of which the record is essential to the object of the survey. In structural studies the relative positions of strata or of other rock masses are the most important facts. The position of an outcrop is a primary fact, which we fix by tying it in to a line of survey that connects all similar observations. The bedding or other structural characteristic is noted next. The strike and dip, by which we may extend the beds along the surface or beneath it, are measured. Next we examine the rock for those peculiarities by which we may identify it with other occurrences or distinguish it from them, and having ascertained its relations, we are prepared to compare its position and attitude with that of other parts of the larger structure to which it belongs.

Let me suppose that an archaeologist is investigating the construction of an ancient building, which is partly gone and partly buried. His notes would relate to measurements of the exposed parts and would consist chiefly of sketches upon which he would record the details. In his mind he would trace out the plan of the buried portions, and upon that foundation he would visualize the original, complete structure. His notes, however, would usually state only the bare facts of directions and dimensions, with such classification of material as would enable him to recognize the part of the structure described.

In looking over old notebooks, I find that I have been that archaeologist, but my notes would seem very meager to anyone else, altogether inadequate as compared with the articles worked up from them. They have sufficed me, however, as records of definitely observed facts and as reminders of the related facts, all of which took their places in the hypothetical reconstruction that grew in my mind as I worked. How much a man should record may be a matter of choice or may be determined by circumstances beyond control; but he may count on it that he will often wish he had put down more or had looked for evidence of which he did not think. In other words, the scope of note taking should be as broad as the scope of observation and inference, but it is always limited, by conditions of time, weather, and companionship, to a fraction of that which should be set down on the spot.

It is desirable that notes be written in printed italics, that is, in a script which is not the usual, illegible handwriting of the college graduate, but a small, distinct lettering. Distinctness is an advantage, even to the man who has to read his own notes, and it is essential if they are to be interpreted by another. A small, or even minute, habit of lettering is required on maps and diagrams. It is advantageous to carry it through all the different classes of notes.

Though written small, notes should be widely spaced, and each separate observation should be set off from others by wider spaces. There should never be any possibility of doubt as to the connection of related statements or the distinction of unrelated ones.

A common source of confusion is the failure to locate an observation. We are pacing a traverse survey over a mountain and are recording the kinds of rocks of which it consists and their relations to one another. We observe, locate, and describe an outcrop. Passing on, we mentally take note of a variety of facts and arrive at the next station of our survey with them in mind, but the immediate observation of the facts at that station usually precedes the recording. The two groups of facts, those observed *since the last observation* and those seen *at this point* are then easily confused in the record. The initials S.L.O. (Since last observation) and A.T.P. (At this point) serve conveniently to separate the items.

Enough has been suggested to demonstrate, perhaps, that taking notes for scientific record is an art, which requires and will repay planning, painstaking care, training, and practice.

There are several systems which have been elaborated on the basis of experience and are adapted to different classes of geologic surveying. The original articles should be consulted.[1]

PURPOSE OF STRUCTURAL FIELD WORK

Although it has been implied in much that has gone before, the purpose of field work for studies in structural geology should, perhaps, be more clearly defined. *Structural field work is measuring the details of the architecture of the earth.*

Measurement must be preceded by recognition of the kinds of materials of which the structure is composed and of their general arrangement in any part of the great structure in which they are imbedded. But we tread unknown ground. We must carry the identification of the rocks and the delineation of their outlines in larger or smaller masses along with the measurement of the attitudes and dimensions. The purpose is to survey—to survey, not the surface, as the topographer does, but the internal arrangement of the strata, or of the igneous or metamorphic rocks, as determined from surface measurements.

The purpose becomes more definite when we are confronted by a specific case. For instance, the delimitation and measurement of the horizontal strata of the wall of the Grand Canyon of the Colorado demands simply vertical measurements of the thicknesses of the strata, but the purpose with which that work has been done has been to afford data for interpretation of the record of geographic changes corresponding to the changes from limestone to sandstone or to shale. The latest survey, by Noble, is an example of the care with which even so simple a type of architecture should be investigated.[1]

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[1] Willis, Bailey, Graphic Field Notes for Areal Geology, *Bull.* Geol. Soc. Am., vol. 2, pp. 177–178, 1891. Campbell, M. R., Rapid Section Work in Horizontal Rocks, *Trans.* Am. Inst. Min. Eng., Colorado Meeting 1896. Kemp, J. F., Geologic Bookkeeping, *Bull.* Geol. Soc. Am., vol. 16, pp. 411–418, 1905.

Or we would ascertain the distribution of anticlines and synclines in a region of open folds, like parts of Pennsylvania or the Jura mountains. We observe the strikes and dips of the strata, identifying as often as possible some selected key stratum, but it is essential that the relative horizontal and vertical positions of the observations should be determined and, to that end, a map must be available or must be made. The investigation of the rocks is thus accompanied by observations for position. Similar requirements are set where the relations of the more irregular, complex rock masses are involved, as in the study of intimately folded and faulted sedimentary, igneous, and metamorphic rocks. The classic work of Albert Heim,[2] that of Peach and Horne,[3] and that of Pumpelly, Wolff, and Dale[4] afford illustrations of the skill with which such investigations should be executed.

Or the investigator may face the task of unraveling the relations of the pre-Cambrian complex, in which the original character of the rocks and their original relations are obscured by subsequent alterations to the extent that the solution defies any but the most patient and penetrating research. The great work of Van Hise and his associates in the iron ore regions of Lake Superior stands as one of the most intensive and fruitful investigations in this, the most difficult, branch of structural geology.[5]

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[1] NOBLE, L. F., A Section of the Paleozoic Formations of the Grand Canyon at the Bass Trail, U. S. Geol. Surv., *Prof. Paper* 131-B, 1922.

[2] HEIM, ALBERT, "Mechanismus der Gebirgsbildung," 1878.

[3] PEACH, B. N. and HORNE, JOHN, Memoir on the Geology of the Northwest Highlands of Scotland, Geol. Survey of Great Britain, 1907.

[4] PUMPELLY, R., WOLFF, J. E., and DALE, T. N., Geology of the Green Mountains, Mass. U. S. Geol. Surv., *Mon.* XXIII, 1894.

[5] VAN HISE, C. R., "Principles of Pre-Cambrian Geology." VAN HISE, C. R., and BAYLEY, W. S., The Marquette Iron-bearing District. U. S. Geol.

It is not within the scope of any single manual to go into the details of the various methods which different observers have used in pursuing the investigation of more or less complex structural districts. In fact no geologist, however experienced, can foresee anything more than the general scheme of his method of attack, until he has entered the field. From the beginning, his ingenuity should be exerted to discover the critical aspects of his problem and to develop a method which will lead most directly to an understanding of its significant facts. The more he knows about surveying, mechanics, chemistry, physics, geology in its several branches, and Nature, the readier will be his invention of method and the more penetrating his insight into the secrets of the mountains.

Nevertheless, experience eventually formulates a certain general method of attack on a structural problem and, although it will always remain an individual method, mine may be helpful to others as a suggestion for the development of their own. My experience has led me to something of the following scheme of investigation to ascertain the general structure of a region, which, although the procedure is not necessarily systematic, had best be presented under successive headings.

PHYSIOGRAPHIC QUESTIONS

Physiography, as I understand it, is the expression of the interaction of the earth-forces with those of the atmosphere, and the physiographic ensemble or landscape of any region is the record of that geologic period during which they have worked together; that is, it is the record of the history of the region since it last became a land area. Many lands retain features which go back to the Cretaceous age. Practically all the mountain elevations of the world are younger than Cretaceous. Hence the physiographic record contains the story of their uplift.

Among physiographic features, streams comprise the oldest

Surv. *Mon.* XXVIII, 1897, and other monographs of the same series by Van Hise in co-operation with Leith, Bayley and Clements.

survivors, or surviving remnants, and also the youngest developments in response to earth movements. They thus embody the longest record of the history of the land. This is not a treatise on stream development and conquest, but certain lines of analysis which bear on structural studies are appropriate.

With reference to the structure of any district, streams fall into three classes: (1) Those which flow in courses bearing no definite relation to the strike of the rock masses. (2) Those flowing parallel to the strike. (3) Those flowing at right angles to the strike.

The first are interpreted as having become superimposed upon bedrock, on which they did not originally grow, or as being older than the mountain uplifts across which they now pursue eccentric courses, or as having been directed in peculiar channels by glaciers or by volcanic lava flows. The conspicuous examples are great rivers, like the Colorado, the Ohio, and the Columbia. Their history is complex and is significant in structural investigations only in relation to broad geographic problems, except where some detail is adjusted to local conditions.

Rivers which flow parallel to the strike of the rocks, or to the general trend of the ranges or ridges, are adjusted to the outcrops of the softer strata or to lines of crushed rock along a fault plane, and they trace out the plan of the structure in so far as it is expressed in the arrangement of the weaker rocks.

Streams that cross the structure at right angles have usually grown upon a slope, parallel with its line of most rapid descent. They took the shortest course to the lowland or to the sea. They had the steepest fall. They were accordingly the stronger and, invading the territory of longitudinal streams, they have captured them, providing they are old enough.

Streams are extremely long lived and very tenacious of life. Those of an older generation often continue to exist in sections as parts of a younger system, by which they have been captured and dismembered. The directions of flow and the angles in the course thus register older and younger controls, which were inherent in the structure of the rocks or due to disturbing earth movements. The stream pattern, therefore, has a direct relation to the facts of structure, as they exist, and to the successive episodes of tilting, folding, and faulting by which the attitude of the surface has been modified. The examination of the pattern, whether on a map or on the ground, is accordingly one of the most immediate approaches to an understanding of the structure.

The principles which govern the growth of streams and the manifold conditions that determine their adoption of a course, as individuals or in systems, should be known to the structural geologist.

The interpretation of structure according to physiographic evidence may also be based on the warped, tilted, or displaced positions imposed upon ancient topographic surfaces, whether they be mature landscapes or peneplains. In this light an old topographic surface is often as significant as a fossiliferous limestone or other well-defined stratum.

It is assumed that the surface is so developed and so distinct from younger surfaces that it can be recognized and identified in whatever position it may survive. Thus many physiographers have seen the Cretaceous peneplain in the even crests of the Appalachian ridges and, to take a very different case, the Pliocene valleys of the Coast Range of California are obviously distinct from those of later development. Each one in its own province affords a means of determining the amount and character of the displacements it has suffered.

On entering a district for structural studies it is desirable to determine whether the youngest structures are alive or dead. In the case of earthquake regions there is no doubt, but even where there is no direct evidence of life the mountain uplifts may be active in the sense that a slumbering volcano is active. Even though the movements be so slow that the idea of catastrophe is excluded, as is generally the case, the movements may be in progress and faulting or folding may be developing. The evidence is then to be sought in the relation of the oldest topographic surface to the underground structure. Does it cut undisturbed across the folded or faulted strata or has it also been warped, folded, or faulted?

In regard to the distribution of structures that are dead and those that are not one may venture a generalization. Countries bordering the North Atlantic, from Florida round through the United States, Canada, Greenland and Great Britain to Germany, are structurally dead; that is to say, the folds and faults which affect the rock masses in those regions were formed and the forces which produced them had ceased to act through that particular mechanism before the Cretaceous peneplain, the oldest topographic surface there known, had been produced by erosion. Subsequent movements of the earth's surface have taken the form of broad upwarps. Remnants of the Cretaceous plain may be detected in the Atlantic provinces and there are many erosion features of Tertiary date, but there is no local ridge or valley which owes its existence to concurrent deformation. The relief is solely an effect of resistance of the harder rocks to erosion.

In contrast, the Pacific borders are structually alive. From Cape Horn via Alaska and Japan to the East Indies the coastal ranges are in active movement. Upthrust faulting is the dominant mechanical effect. Some thrusts, like the San Andreas fault, are at present very much alive. Others are dead. The living are distinguished from the dead by their relation to the Pliocene topographic surface, which is displaced by the former, but which extends without offset across the latter. In California and no doubt in other mountainous lands, there are certain large mountain masses, of very complex internal structure, surrounded by live faults. Over their summits, at a high elevation, stretches the gently modulated Pliocene landscape, eroded across folds and faults of the first magnitude. They are evidently older than it is and have been inactive during the period of its completion and elevation to its present position. But the Pliocene surface is cut by the marginal faults and is displaced along them. Sometimes it has simply lagged behind as the surface of another, less elevated block, sometimes it has been depressed by the downward rotation of the mass that underlies a valley. Sometimes it is not faulted, but is bent down in a convex mountain slope and passes beneath the valley as a syncline. It then is a folded erosion surface.

The geologist who possesses an eye trained for physiography can read the active structure of a live country as he scans the landscape. Most students, however, are taught in the dead lands and the appearance of a live mountain or thrust fault is unfamiliar.

Another clue to the structure of a district is to be found in the distribution of hard and soft strata and other rock masses, as brought out by erosion. It is a very old and well-known clue, but is not always employed with the penetration that makes it most useful. It rests upon the principle that a resistant rock is represented by a ridge or hill and a yielding one by a valley, provided that the surface has been modeled by erosion. The form of the ridge, and sometimes of the valley, more or less definitely expresses the attitude of the strata, exhibiting dip slopes or jointed faces, and thus indicates not only the extension of the stratum, but also its position in reference to the structural axes of the area. The discontinuity or abrupt ending of a well-defined feature is especially significant, and this applies to the vertical dimension as well as to the longitudinal.

Thus, for example: A deep valley crossing the strike of a monotonous mass of slates retained an even floor where it cut through a high ridge of quartzite. From the road in the valley the quartzite could be seen to be dipping about 60 degrees, but it did not cause any cascade in the stream nor appear in the road banks. Therein was the evidence of a fault —a fault of some kind because the quartzite was cut off before it reached the valley floor; probably a thrust because the angle of dip of the fault must be considerably less than 60 degrees to cut across the thick bed before it could get down, in part at least, to the valley floor. The alternative of a vertical fault was entertained, but not for long after examining the crushed and slickened rock of the lower part of the quartzite. Thus the type of structure and the position of what afterward proved to be an important thrust were fixed in driving into an unknown, forested mountain district. (Fig. 123.)

The use of physiography as a key to the interpretation of structure thus falls into three categories: the study of stream patterns, the identification of old topographic surfaces in inconsistent positions, and the explanation of the distribution of hard and soft rock masses as brought out by erosion. Given good maps, the method can be applied in a preliminary way by inspecting them. Its efficiency is directly proportioned to the geologist's understanding of the principles and processes involved in the development of landscapes or of the details of streams, hills, and valleys.

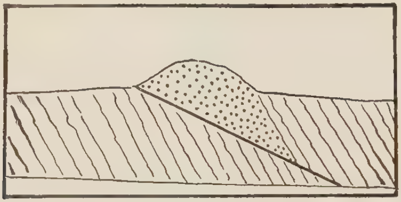

FIG. 123.—Overthrust postulated on evidence of a valley crossing a quartzite ridge without change in the grade of the valley floor.

Both efficiency and confidence grow with practice and extensive observation.

METHODS OF SURVEYING

While physiography may be employed to very great advantage as a means of interpretation of the structural features of any view, it does not afford measures of form or dimension. For that purpose surveys must be made. There is also the necessity for intimate observation of the kind, attitude, and mechanical condition of the rocks, which demands that the geologist shall get close to them. This involves going from point to point, usually on foot and the more on foot the better.

Surveys for topographic or mine maps must be executed with the plane table and alidade, transit and stadia, or other instruments which give results that are up to civil engineering accuracy. The geologist is fortunate when such maps have been made. If not, he should know how to make them if necessary, but topographic surveying cannot advantageously be combined with geologic surveying. The two operations should be carried out separately, whenever possible. They are incompatible, the former being precise, instrumental measurement, the latter consisting of observation and interpretation of natural phenomena. Both demand close attention and neither can be performed properly with divided attention.

For this reason instrumental work should be reduced to the minimum in geologic surveying. Methods of approximation should be used wherever they lessen the demand on attention for determining accessory facts, and methods of checking approximate results should take the place of too constant application of the mind to securing more precise measures.

For measuring distances, whether traversing roads, mountain trails, or pathless slopes, the wheel or the pace is the unit most readily available. The former is limited, of course, to passable routes, generally roads, although an adaption of the wheelbarrow can be used on paths. The pace has no limitations as to its availability in time or space.

Pacing is stepping off a distance, and as it is usually conceived is a burdensome process. Pacing when practiced until it becomes a habit is simply walking with a subconscious knowledge of the number of steps taken and does not materially distract from other observations. In order to reduce pacing to walking one must take one's natural step. In order to reduce counting to a subconscious rhythm, it should come at not too frequent, but fixed, intervals. These objects are accomplished by walking as usual and counting every fourth step. My pace is thus $11\frac{1}{3}$ feet, numbering 460 to the mile, or 290 to the kilometer. Another's may be 10 feet or 12. It does not matter what it is, provided it is the sum of four convenient, customary steps.

Starting out with the left foot, the count runs naught, naught, naught, one, and ends on the right foot. When the count of ten is reached, the pacer, instead of saying the third naught, says one, thus: naught, naught, one naught. Similarly, twenty-five would be naught, naught, two, five. When a hundred is reached, the hundred digit takes the place of the second naught. Thousands are counted on the first step. It will be found then, that units fall on the right foot, tens on the left, hundreds on the right and thousands on the left. This distribution is a help to the habit of automatically registering the hundreds and tens, which are easily skipped when counting every step.

Walking on roads or trails, or across grassy plains, there is no difficulty in keeping a natural step of average length, but up or down hill, rough ground, boulders in a stream bed, underbrush and windfall, or snow, require adjustments.

Ascending or descending a slope which invites one to lengthen one's step, it is better to shorten it intentionally and to count six steps instead of four to the pace. When the slope is one on which you turn the feet out to get a better grip, eight steps to the pace may be counted. In any case the pace remains unchanged in length. Similarly, six or eight steps may be counted to the pace to reduce the length of a winding path to the length of the straight sight across the bends. This requires practice in estimating the ratios of diagonal lines to the side, but it pays in the saving of many short sights.

When the obstacles to ordinary walking are such that paces cannot be stepped off directly, in climbing through underbrush or jumping from stone to stone, etc., recourse may be had to eye-estimate of paces. This requires attention. One casts the glance ahead at each pace to a stick or stone which lies a pace (four ordinary steps) in advance, and counts the pace on passing it. The method enables one to carry a fairly close estimate of the distance traversed over ground that defies any other means except stadia or triangulation, and in forests where a line would have to be cut out for them.

Pacing, like typewriting, is a question of much practice and requires attention until the subconscious reaction of the mind to the swing of walking is established; but it can be practiced in the daily happening of going somewhere. Once acquired, the habit is not easily lost and constitutes a valuable asset for the geologist, since it is always instantly available, anywhere. Artificial aids, such as counters, should be avoided. Their use implies a weakness, which should be overcome by exercise.

Time-traversing is a method of observing distances which is much used in general exploration and may advantageously be employed where pacing is out of the question. It is based on the estimate of the rate of progress between each two points at which the observer pauses and upon notations of the exact times of departure and arrival. The elapsed interval multiplied by the rate of progress per minute or per second gives the distance. A somewhat steady rate of advance over somewhat long stretches is desirable in using this method. It has been employed by Russian explorers, and the maps of Mongolia are to a very considerable extent drawn up from route maps made by them in this manner while riding horses or camels. Dr. Hamilton Rice has employed it in extensive surveys of the Amazon and Orinoco basins by launch and has recently called my attention to a device, consisting of two scales drawn on two sides of a right angle triangle, which does away with the necessity of multiplying. On a horizontal scale lay off distances; on a vertical scale lay off times in minutes and seconds; draw an hypothenuse to correspond to the rate of travel, or to various rates. Then the distance corresponding to any time elapsed may be read off by following the horizontal across to the hypothenuse and noting the distance on the scale at the top.

Time surveys have for the geologist the disadvantage that the psychology of the method is opposed to his purpose of detailed observation. Seconds become altogether too numerous when noted as such, yet if an observer hesitates thoughtfully over an outcrop they may be of great value.

Compass-sighting and revolver-shooting are comparable actions, with which the ranging of the transit or heavy gun is in strong contrast. A compass mounted on a tripod is as much out of place as a revolver on a gun carriage. In each case the freedom of handling for which the implement was designed is sacrificed.

The geologist's compass may be held in the hand, at a convenient focal distance from the eyes, about the level of the belt, and be directed on the desired course without looking through the sights. The ability to do this within the limit of error permissible in geologic traversing is readily acquired by practicing ranging of near and distant objects in a straight line. The graduation of the compass should be one that can be read at the distance at which the compass is customarily held. The needle is best read by halving the swing while it is in motion, but may be allowed to come to rest if that is found necessary in order to be sure of getting the sight in the right line. The permissible error in good traversing is plus or minus 1 degree, or 20 feet at a distance of 500, provided that the scale on which the sight is to be plotted is not larger than 1,000 feet to the inch, 1 : 12,000.

In plotting the observed course on the field sheet there are three operations: laying off the angle, drawing the line, and scaling off the distance. The manipulations are reduced to their simplest terms by abandoning the protractor and using as a ruler and scale a strip of paper torn out of the notebook and folded so as to give a straight edge.

The protractor can be dispensed with, provided one knows a few ratios of coordinates, corresponding to the natural tangents of certain angles. Thus:

1 : 10	6 degrees	1 : 2	27 degrees
1 : 6	10 degrees	4 : 7	30 degrees
1 : 4	15 degrees	2 : 3	34 degrees
1 : 3	18 degrees	5 : 6	40 degrees
4 : 10	22 degrees	1 : 1	45 degrees

These may be laid off across the reticulated page either from the horizontal or vertical, and may be used for any one of the angles enumerated or for its complement. If the observed angle is not one of those whose ratio is given, the actual angle can be plotted by estimate between the positions of those on either side of it.

The methods of sighting courses with the free compass and of plotting them by coordinates are methods of approximation and are subject to the limitations imposed by conditions of adequate accuracy. These reduce themselves to two—the scale on which the traverse survey is plotted and the closeness with which it can be checked. In general geologic surveying the scale of the field map ranges from 2 miles to 1 inch (1 : 125,000) to 1,000 feet to 1 inch (1 : 12,000). Now, if our sight is not more than $\frac{1}{2}$ inch long, when drawn in the notebook, an error of 1 degree on either side of the true line will fall within the width of a pencil line, or as close as we could draw an observation, however accurately observed and noted. But $\frac{1}{2}$ inch on a scale of 1 : 125,000 is 1 mile, and on 1 : 12,000 is 500 feet. These are distances which will rarely need to be exceeded in traversing on the scales indicated or on any intermediate scales.

In plotting courses the notebook may advantageously be held in the left hand with the fingers under it and the thumb holding the paper scale firmly on the page. The further end of the scale can be steadied by the little finger of the right hand, while the line is drawn with the pencil held between the thumb and two fingers. In order to avoid erasures, the line should be no longer than the sight is known or is estimated to be.

The closure error of traverses run in this manner by pacing, sighting with free compass, and plotting by coordinates, varies in my experience between 1 and 5 per cent of the distance run, according as the line followed roads or winding trails or over mountains without a trail. In any case where the data are part of a map they should be checked by more accurate locations. The surveys necessary to get the control should, however, be executed separately from the geologic study, so far as possible.

The geologic traverse, which is plotted in the field, is often second in importance to the deductions it immediately suggests. If the investigation has been conducted for the purpose of getting an understanding of the structure, the traverse has served a major object in the development of that understanding, for each observation of strike and dip, or of the occurrence and classification of an outcrop has been located as made. The plan of the structure and the data for constructing the cross-section of it have been delineated. And interpretation has gone forward according to the assembling of the facts, as it could not with mere verbal descriptive notes.

OBJECTS OF SURVEY

In order that a particular geological survey should be conducted with efficiency to a result that shall satisfy its purpose, the methods of execution should be adapted to that end. This means that the geologist shall consciously classify his purpose and plan his method accordingly. It is convenient to distinguish reconnoissance, general, and special surveys.

Reconnoissance surveys are made under conditions which impose the requirement of large scope and allow only relatively short time. Thus a prerequisite of success is efficiency. But to be efficient one must be both trained and prepared for the particular study proposed. For this reason reconnoissance requires experienced men.

Any study may be begun by a reconnoissance, whether it is to be conducted in the laboratory or in the field, the purpose being to obtain the data on which to plan a more detailed investigation. From one point of view a college course is a reconnoissance of the field of knowledge for the purpose of discovering the branch or branches in which future specialization shall be undertaken. Or an Edison may test a greater variety of materials to find that general class which is most likely to repay the labor of more thorough experimentation. Or an explorer may traverse an extensive country, gathering general information on which future journeys shall be planned. In each case the object is similar: to lay the foundation for more intensive work.

A geologic reconnoissance is, as a rule, a rapid survey of a region too large to be covered thoroughly. Preparation for it should include the study of what is already known and a digest of this in accessible form for the journey. What another has seen has a special interest in the light of his description and may lead his successor to a further step. It is also true that the unknown is infinitely more difficult to observe than that for which we are somewhat prepared, however slightly. The fact is too evident to require elaboration and too often neglected to be passed over unmentioned.

Where surveys are to be carried out rapidly, but not hastily, system is essential. The kinds of observations to be made and the methods of making and noting them should be considered in advance. The observer, the methods, and the means should be coordinated and the work should be practiced.

In the field, in course of the reconnoissance, there is constant need of the exercise of selective judgment. The capacity to pick out the essential from innumerable and varied opportunities for observation is the prime qualification of a good explorer. And with this selective ability should go that understanding of facts which will enable the observer to recognize those that are of more than general importance.

Because haste is commonly imperative in reconnoissance and most of the observation must be incomplete, if not superficial, *it is necessary to pause occasionally with the definite purpose of doing something thoroughly.* That something should represent a critical fact, such as the thickness and normal sequence of strata, and it should be observed with all possible care. A few such observations serve as a framework on which to hang the less substantial ones and give permanent value to the whole result. The spirit of the explorer is usually impatient of delays for detailed work. He sees limits set to the wide fields he hoped to range, he is carried on by his own impetus; but, if he wishes his work to stand future investigation or to be worth what it costs in time and money, he will take time to build some solid facts into its foundations.

The execution of a geologic reconnoissance should be intrusted only to a geologist fitted by physique, personal qualities, and experience, for the task. The exploration of Alaska, which has now been prosecuted with remarkable efficiency for 25 years and is passing into the stage of more detailed work, is an example of the wise application of that principle. It has been executed by picked men.

Personal qualifications fall under the four heads of physical fitness, mental fitness, morale and experience.

It goes without saying that an explorer should have a sound body, but more than that he should have special qualifications, appropriate eyesight, for instance. A near-sighted man cannot advantageously observe the outlines, color distinctions, and detailed forms of mountains, upon which depend inferences regarding their physiographic history and structure. Whatever the environment of the proposed work may be, the geologist should consider himself as he does any other item of equipment and should see to it that he is physically fit.

Mental alertness is a prime requisite for efficiency under pressure of time and circumstance. With it should go decision. In practical matters these should be governed by common sense, and in scientific inference by the habit of toleration. The observer who is intolerant of alternative hypotheses will not maintain an unbiased opinion. The capacity to entertain several views or interpretations of partially understood and incomplete groups of facts is indispensable, if the work is to be sound. Mental alertness and mental honesty should go hand in hand.

As regards morale the explorer should have the pluck of an American and the self-respect of a Chinese. It comes to the same thing, for the American's pluck is an expression of self-respect, and the self-respect of a Chinese demands similar determination. The two may be distinguished as self-reliance and reliability. Their combination, associated with cheerfulness, fair-mindedness, and kindliness, constitute 40 per cent of the qualities that a good explorer should possess.

If now we allow another 40 per cent, about equally divided, to physical and mental fitness, we shall have left 20 per cent of the sum of the qualifications of a well-equipped man, and this we must assign to training and experience. Both training and experience should be as broad as possible. However special the certain object of an exploration may be, there will always be many collateral, and often intimately related, lines of observation which can be pursued to advantage. Assuming that the major subject to be studied is the geologic structure of the Himalayas, for instance, the geologist should know physiography, stratigraphy, paleontology, and petrology, in addition to being specially grounded in the structures of mountains. His knowledge of the collateral lines may not be allembracing, but he should know how to read the facts which they present, at least to the extent of being able to observe them and record them correctly and intelligibly. His command of auxiliaries, if we may so designate related branches of knowledge, may advantageously be even wider, including the geography of the human races, social customs, and language. If his object be related to the resources of a region, with a view to their valuation, his grasp of the problem should include economics, commerce and financing. He is then, however, no longer primarily interested in structural geology, although that branch of observation may hold the key to the situation, as it does in the investigation of many oil fields. He has become a fully equipped consulting geologist.

A specialist is not infrequently chosen for reconnoissance, breadth of study being sacrificed to intensive investigation. The situation which then arises is, however, an illogical one, since the habit of thought of the specialist is usually one which unfits him to observe comprehensively, in the large. Accustomed to laying bricks in his mental structure, he cannot build with great monoliths. The only specialist who can successfully cope with the problems of reconnoissance is a specialist in reconnoissance.

In the preparation of physical equipment the categories relating to clothing, bedding, food, shelter and transportation are intimately related with one another and with the conditions of life in the region to be explored. Each case must of necessity be considered in the light of what is known or may reasonably be inferred regarding the circumstances. Experience, however, dictates one principle of general application. The explorer may better adapt himself and his ways of doing things to those of the country and people than to try to convert the people to those which seem to him handier. This applies especially to equipment which must be handled by the natives of the country. I have known an expedition to break down because pack saddles, made by a saddler who never saw a burro, caused sore backs, where the native packers could have made good with their rude but accustomed outfit. Even personal habits with respect to food, clothing, and bedding may wisely be modified voluntarily, but always within the limits essential to health and efficiency.

The discussion of preparation for reconnoissance has diverged somewhat from the purpose of the chapter, the application of structural geology to certain aspects of geological work, but the diversion is perhaps, not inappropriate, since reconnoissance is an important method of survey by which to ascertain the larger features of geologic structure.

A general survey may be so described because, within the area which it covers, it is supposed to include all aspects of the local geology. It differs from a reconnoissance in the two respects that it is thus all inclusive and that there should be sufficient time allowed to permit the geologist to assemble all the facts bearing upon the problems he discovers. Good examples of this class of work are to be found in the folios of the Geologic Atlas of the United States.[1] Those enumerated in the subjoined list illustrate a great variety of general surveys, in areas where the problems are of broad geologic interest and the geologic structure plays an important rôle. It is to be noted, however, that work of this character is mainly descriptive. It thus differs from what we may call monographic study, since the latter purposes to carry on the investigation of the assembled facts as a research into their more fundamental relations and causes. The general survey thus stands between the preliminary reconnoissance and the more or less final monograph.

The methods which may be employed to attack the study of a district with reference to its structure are more detailed and complete in a general survey than in a reconnoissance. The reconnoissance, however, may well precede the detailed survey, and the methods of field observation may therefore be stated in sequence. They would be practically the same at first for both objects.

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[1] See, for instance: No. 30, Yellowstone National Park, Wyoming; No. 31, Pyramid Peak, California; No. 36, Pueblo, Colorado; No. 62, Philadelphia, Pennsylvania; No. 71, Spanish Peaks, Colorado; No. 78, Rome, Georgia; No. 83, New York City, New York; No. 94, Brownsville-Connellsville, Pennsylvania; No. 131, Needle Mountains, Colorado; No. 139, Snoqualmie, Washington; No. 142, Cloud Peak—Fort McKinney, Wyoming; No. 149, Penobscot Bay, Maine; No. 151, Roan Mountain, North Carolina, Tennessee; No. 196, Phillipsburg, Montana.

In the hypothetical case to be considered, the geologist is approaching and entering a district where the rocks are so exposed that he may observe their general character and attitude. He will begin to ascertain that he has to deal with sedimentary or igneous or metamorphic rocks, or with more than one of these classes, and the possible types of structure will be suggested.

Even before he has recognized the rocks, while he is viewing them from a distance, the physiographic aspect of the country has given him a clue to the later history of earth movements. His eye ranges from canyons to high-level, old valley floors and from these up to summits which, by their acute or rounded forms, by their equality or inequality of summits, suggest the degree of preservation of an earlier topographic phase. If not these particular features, then others may be noted and questioned as to their meaning. It was thus that from a tower of the Great Wall of China, I first scanned the Wu-t'ai-shan, a fore-range of Tibet, and began to read the physiographic history of that great uplift.[1] (Fig. 124.)

Before we reach the point whence a broad view may be had, the route of ascent will lie in a canyon, or up a spur, or over a slope, but in any case must pass some outcrops of rock upon which observations can be made. Any geologist will pause to break the rock to ascertain its character. A structural geologist should examine its structure, taking the strike and dip of the stratification or of obvious joints. These afford the first suggestion of the directions in which forces have acted to produce the structure of the mountain.

As one proceeds, notes of this suggestive character accumulate, but they lack coordination unless their mutual place relations have been determined. It is here that the habit of surveying is found useful, particularly the habit of carrying a traverse by pacing and compass. By Ford or horseback is a much less satisfactory mode of progress than walking, where the object is to observe

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[1] "Research in China," vol. I, part I, p. 208, Plate XXX.

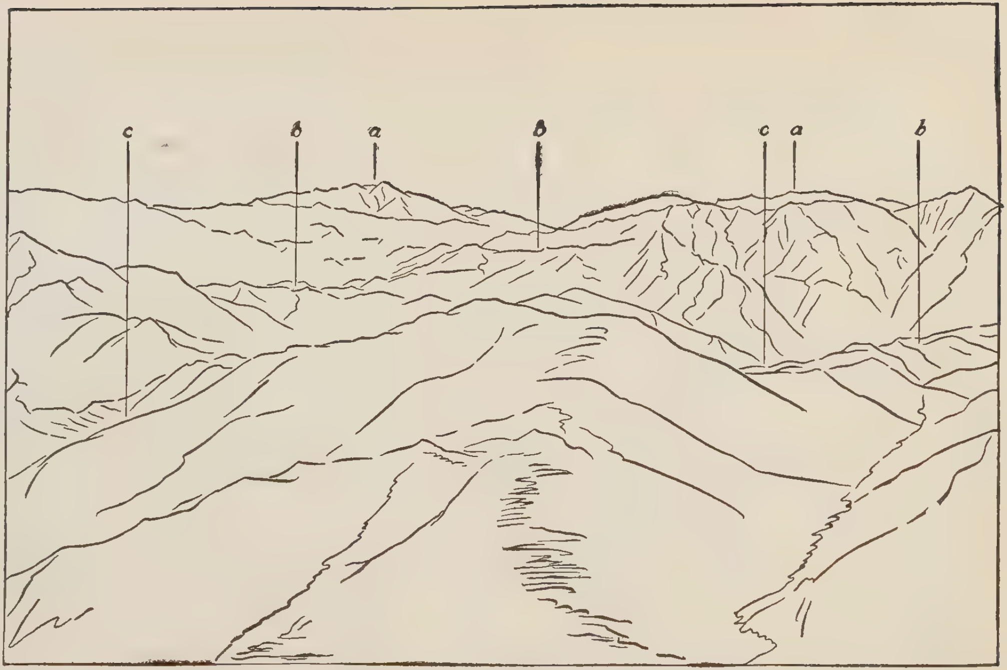

FIG. 124.—View of the Wu-t'ai-shan Range, Shansi, China, showing topographic features and their relation to the stages in its development. *a*, the oldest stage, an ancient peneplain forming the highest summits; *b*, ridges representing the level of valleys in a second stage of mature erosion; *c*, the young gorges of the present cycle of erosion following the uplift of the mountains to their present level.

rocks or landscapes. They are passed too swiftly and the inertia opposed to dismounting is too great. Assuming that the geologist is afoot, he should begin to pace from the first point of observation, in order that he may locate that structural note with reference to all those which are sure to follow. Beginning thus at any undetermined place, the traverse line will be in the air until it is tied in to a crossroads, stream fork, or mountain peak, that is to some identifiable feature. By continuing it, this object will eventually be accomplished and all the points of observation on that line of route will be known.

The necessity of coordinating any structural observation with others by determining the relations in space should not need emphasis. Only by so doing can the forms and dimensions of structures be ascertained. Verbal notes lack this essential statement of place relations and therefore cannot take the place of the graphic notes that are linked together by the traverse line.

Circumstances may preclude the possibility of plotting graphic notes continuously in the form of a traverse, while yet permitting pacing and compass sighting. The distances and courses may then be set down in systematic notes, to be plotted at the earliest opportunity. If the traverse be interrupted it should nevertheless be renewed in such sections as conditions permit. Afterwards it may very likely be found that those sections contain all the definite information obtained.

If a piece of traverse cannot be run to a known point, the position of any station on it may be fixed by sights to two points whose positions are known. Greater certainty can be secured by observing three points. The observed compass bearings can be plotted on transparent paper as lines radiating from a point and placed over a map. By shifting the paper about till each of the lines passes through the point to which it was sighted, the location of the station sighted from becomes known. Triangulation methods of this type are peculiarly helpful in reconnoissance where the requirement of rapid progress is all important. There is then grave danger that the observer may be stampeded into neglecting some valuable observation because he feels that it will not be possible to locate it. He should make it nevertheless and, traversing to some point of outlook, he may fix it by three sights.

It is a common custom among geologists to have a topographic map enlarged photographically in order that it may be big enough to permit of making notes directly on the enlargement. There is an apparent gain in convenience, which may be real enough to justify recourse to the method in individual cases, but there is a real loss which is often not so apparent. The supposed gain lies in the assumption that points at which observations are made may be located on the enlarged map without the labor of making a traverse, but with sufficient accuracy to satisfy the geologist's purpose. The conditions are, however, not favorable. The map, however accurately drawn for its original scale, is no longer accurate as to positions or complete as to details when enlarged. The generalizations which were required by the smaller scale are too obvious on the larger. The omissions become sources of confusion. The features of the map have lost much of their individuality by the broadening of the lines.

To these drawbacks is to be added the more serious one that the geologic facts do not stand out clearly from the maze of lines on the map as they do from the manuscript plot of a well-balanced traverse. The object of taking the graphic notes is lost by making them over other lines, and this loss is most felt during the progress of investigation.

Assuming that the geologist plots his observations of the characters, strikes, and dips of rocks in relation to a traverse line, which he runs as he goes, he sees developing on the notebook page a plan of the structure. The rocks, their variations, likenesses, differences, and significance concern him most. But their attitudes, which express mass relations, are next. Let the section display a sequence of sedimentary beds which exhibit a decided dip. They may be right side up or upside down, so far as the dip determines. The dip changes, becoming gentler or steeper, or the strike swings, in successive observations. A flexure or fold is indicated. Attention is directed to locating it and the axial line is looked for. Its position is an important fact because it sets a limit to the section which can be seen. Its character, whether synclinal or anticlinal, determines whether we have been ascending or descending in the sequence. Its pitch fixes the succession of the strata in a longitudinal direction to right and left.

In approaching a large, possibly complex, fold we may observe a little one, perhaps no larger than a hand specimen. Therein lies a clue to the attitude of the larger structure, which may be too large to observe directly without much labor, for it is a rule that *the pitch of minor folds agrees with that of the complex fold of which they are part.*[1]

The magnitude of the fold is not discernible, as a rule, at the axis. Any sharp fold appears small if we can see only the immediate bend. The size depends on the length of the limbs and the thickness of the strata. We may have observed the latter in approaching the axis and know, accordingly, the importance to be attached to the fold.

On passing the axis of a fold, whether it be an anticline or a syncline, the strata should repeat in inverse order to that in which they were encountered in approaching it. Thus we may have noted the beds in the order *a*, *b*, *c*, *d*, but beyond the axis they should recur in the order *d*, *c*, *b*, *a*. If the fold be a simple, unbroken one, the sequences should be the same on opposite limbs. If they are not the same, we have crossed a fault or an unconformity.

The distinction between a fold, a fault, or an unconformity is not always clear in a single section and may remain obscure until the line of outcrop, along which the evidence must be sought, is carefully studied. The criteria to be looked for are stated elsewhere.

We are *en route* to a summit from which we may obtain a general view. We carry the traverse to the point and thus know where we are with reference to the rock masses which have been crossed. We know their strikes and dips. We can therefore identify them with the ridges or valleys to which they give rise and can interpret the landscape in terms of its anatomy.

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[1] PUMPELLY, RAPHAEL, and DALE, T. N. Geology of the Green Mountains. U. S. Geol. Surv. *Monograph* XXIII, p. 157, 1894.

The explorer who thus looks out from some peak that commands his unknown route may feel the thrill of discovery. He may never see that view again. It therefore behooves him to study it thoroughly, to exhaust its indications, and to record his observations in more or less elaborate outline sketches, with bearings and verbal descriptions. It is hardly possible to overestimate the value of carefully noted facts, which later serve to bring the scene clearly to mind.

The ability to read a landscape in terms of its history and underlying structure now serves a geologist as his knowledge of German should in reading the classic work of Heim. He will recognize three classes of intimately related facts: the effect of the observed rock masses on differential erosion; the survival of areas of an older topographic phase, or of several such; and the activity of warping or faulting during the more recent geologic epochs.

With reference to differential erosion he will trace out the extensions of those strata which he has noted during the ascent, and they will furnish the ground work of his inference beyond what he can definitely recognize. Had he arrived by aeroplane or, what amounts to the same thing, without observing the visible facts along his route, he would be without this firm foundation. When, however, he knows that a certain sandstone maintains a certain ridge, he can follow the sandstone by the ridge. Or he sees that a certain sequence of shale and limestone gives rise to extensive valleys, as observed in crossing them. Then similar valleys in the same region are presumably underlain by that group of strata.

In such inferences there is always the possibility of error because the stratigraphy is, as yet, only partly known, and there is the probability that there are two or more sandstones or several groups of weaker rocks. Alternative hypotheses thus arise. They stimulate observation. We begin to look for differences as well as likenesses.

The concept of differential erosion dates from Hutton, who first recognized it prior to 1785, and the application of it to the study of structure has been more or less consciously the habit of every geologist who has pondered the relations of erosion to the rocks in the field. It is otherwise with the recognition and use of an old topographic surface as a datum by which to identify changes of level and attitude of mountain masses. The names of Powell, Gilbert, Davis and Hayes are associated in the development of that method.[1]

As we look abroad from our point of vantage, we see what we may have observed during the ascent, that the valleys widen by steps. At least, that is a common habit of valleys in most mountain ranges. There is the inner canyon, distinguished by narrowness and the comparative steepness of the slopes. There are terraces or terrace remnants with leveled floors of rock beneath soil or gravel. There are sometimes two or more such evidences of an old valley floor. And there is the upland, which represents the more or less completely finished peneplain or mature surface of an earlier topographic cycle. These are witnesses of the intermittent activity of the uplift, which has raised the mountain range where formerly there stretched a lowland.

One of the most perfect examples of an uplifted surface is the peneplain which has been traced over the Appalachian province by Davis, Hayes, and Campbell. It was a very flat plain before it was warped and it has been warped to a very broad arch, without any notable local disturbances. It has become a classic example, by reason of its accessibility and of the thoroughness with which it has been described. Consequently it is the established type of a warped topographic surface. But because it was so flat a plain, because it has been so broadly warped, it is not representative of many other surfaces of erosion, which were not so perfectly finished and which have been more sharply warped, bent, or faulted on a smaller scale.

It is always fair to ask a landscape: what are your oldest features and where do they survive? The Cascade range of Washington, the Sierra Nevada and Coast Ranges of California, the

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[1] Powell, J. W., "Geology of the Uinta Mountains," 1876; Gilbert, G. K., "Geology of the Henry Mountains," 1877; Davis, W. M., "Rivers and Valleys of Pennsylvania"; Hayes, C. W., and Campbell, M. R., "Geomorphology of the Appalachians," 1894.

Andes of Patagonia, the Alps, the Apennines, the Carpathians, and the mountains of central China, have all answered by presenting a hilly surface, having a relief of several hundred feet but representing a mature surface of erosion, as their oldest surviving feature. They bear it on their broader summits, of course, but they also exhibit it on slopes which may be gentle or steep, and it sometimes extends down beneath wide valleys, from under which it rises again on the other side in true synclinal fashion. Where a slope is faulted, it can be traced like a sedimentary stratum across lower hills to the face of a mountain range, against which it ends. Its further extension is to be sought on the summit of the range.[1]

The identification of an erosion surface, which is no longer at the level or in the attitude in which it was formed requires discriminating care. Alternative explanations of the apparently older peneplain should be hospitably entertained and tested. More than one view of the landscape should be studied. The flat light of midday should be avoided, because it runs the distinctive shapes together, and the long shadows of morning or late afternoon should be awaited, because they bring out the forms.

Is yonder broad, rather flat-topped mountain a mass which carries a remnant of a peneplain? If so the topography of the summit should agree in development with that stage of planation. The soil should be deep, leached, and well oxidized. The valleys should be wide, filled with alluvium, and occupied by meandering streams. The low, soil-covered elevations should consist of the harder rocks, and the softer rocks should be buried. This is a group of criteria which pertain to a lowland plain or to a mature surface of erosion. They are decidedly not appropriate to a mountain top. If they all are present and characteristically developed, the inference of uplift since the surface was eroded is well sustained. It becomes conclusive when supported by observation that the general flattish surface is eroded across rocks of unequal resistance, is in fact a true peneplain or mature surface of erosion, such as can form only at a low elevation.

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[1] WILLIS, BAILEY, Report on an Investigation of the Geological Structure of the Alps, Smithsonian *Miscellaneous Collections*, vol. 56, No. 31, pp. 7–9, 1912.

We feel less sure when the flat-topped mountain is a table mountain or mesa, composed of flat lying strata and perhaps surrounded by a rim-rock cliff. Then it is evident that the structure of the mass is favorable to the development of the form. Wind blowing away soft shale, for instance, may leave a hard table of sandstone, which simulates a plain of old-age erosion. This obvious case may serve to suggest the alternative explanation which rests on the influence of structure. When the topographic surface coincides with a rock surface, which is of such a character that it may be the cause of the topography, the inference of that causal relation is more direct than any other. It should therefore be tested by an appeal to the actually operative agencies of erosion, to determine whether they are competent to produce the observed facts.

In my experience, small topographic forms are often related to and due to the characters of small rock masses. Extensive topographic flats, on the other hand, are usually not the result of rock character, because the latter is too local and changeable.[1] The coincidence is found to be more apparent than real when the strata are traced over a wide area. The outcrops of the bedding planes are then often seen to cross the plain of erosion, with which the dip of the strata makes a small angle.

That long smooth slope which descends from the even-topped ridge to the flood plain of the valley over there does not explain itself at once. Accustomed as we are to consider all valleys as valleys of erosion, that is, as excavated in softer rocks, we would usually call the slope an erosion slope. Its story is then very simple. As the general upwarping of the region progressed and the streams sank their channels into it, there developed a canyon wall, which receded to a mountain slope and became ever lower as the cycle of erosion progressed toward its more advanced stages. In homogeneous material, such as a thick body of shale presents, the slope will tend to be the same along any given contour, especially if one looks along the lines of spurs. From valley to summit however, the profile will increase in steepness, according to a curve that is *concave upward.* If the material is not homogeneous, a mass of schists intruded by dykes for instance, every difference of resistance to the processes of weathering and erosion will be brought out by an accent of relief, for differential erosion has been active ever since the canyon wall was bared. The ravines which score the slope will also be significantly developed. They will have grown like gullies, with vigorous growth of the little trunk gully, but only very slight development of laterals, and the latter will tend to flow decidedly down the slope, instead of along it parallel to the strike of the bedding. The junctions will be acute-angled, not right-angled.[1]

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[1] Smith, G. O., Contributions to the Geology of Washington. U. S. Geol. Surv., *Prof. Paper* 19, 1903.

The ridge crest may be of the Appalachian type—level, even, and far-stretching, interrupted only by occasional wind or water gaps—and it will then be recognized as the intersection of the slope with an ancient plain. Or the ridge may be broad and somewhat hilly on top, presenting a surface which may be interpreted as very young or very old or a combination of young features with aged ones. In some mountains the summits are all acutely sculptured by frost and ice and water, till there is nothing of the preceding cycle left, save perhaps an approximation of peaks to a common level.[2] The actual features are then all young. Elsewhere a broad ridge partakes of the character of an uplifted peneplain and exhibits its aspects. This is very commonly the case in the Coast Ranges of California, the mountains of Central America, and those portions of the Andes with which I am familiar.[3] It is also a feature of common occurrence in Europe, in the active young ranges of the Alps, Apennines, and Carpathians. Or the young headwaters of older streams may have pushed their canyons back into the remnant of the peneplain so as to combine recent and ancient features in one landscape. Such an association is of very general occurrence, where the modern cycle has not yet destroyed all the features of the older.

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[1] This type of erosion slope is well illustrated along the Allegheny Front and elsewhere in the Appalachian province. See, for instance, the mountain on the east of Poor Valley, Mercersburg quadrangle, Pennsylvania.

[2] Willis, Bailey, Contributions to the Geology of Washington. Deformation and Physiography of the Wenatchee-Chelan District, Cascade Range. U. S. Geol. Surv., *Prof. Paper* 19, plates, 1903.

[3] Willis, Bailey, Physiography of the Cordillera de los Andes. Intern. Geol. Congress, 12th Session, *Compte Rendu,* pp. 733–756, Toronto, 1913.

Let us now look again at that long smooth slope which connects the valley and the ridge over there. Is it necessarily an erosion slope, sculptured in its present position? Or is it perhaps an older surface, tilted or bowed up into an attitude which is inconsistent with its original form? If the latter be the case what is the effect of the work of erosion in remodeling the surface? Questions such as these cannot lightly be put aside without weighing the evidence for or against the hypotheses they suggest. They first took definite form in my mind while studying the eastern shore of the Adriatic from Fiume south, and I have since found them very fruitful.

Consequent streams flowing down a tilted peneplain resemble those which develop as gullies and ravines in a slope due to modern erosion. They also flow straight from ridge to valley. But they are not so simple. Rivers of the earlier cycle existed there before the consequent streams were born, and the older generation had long since become adjusted to the structure. In most cases that adjustment had resulted in channels which run parallel with the trend of the range, at right angles to the courses of the consequents. When uplift occurs, the older streams are usually not accelerated to a degree sufficient to enable them to compete with the newly developed consequents, and they are therefore captured by the latter. The resulting river systems, or rivulet systems, are characterized by a rectangular plan and flow through valleys and canyons, which differ in development as maturity differs from immaturity.

The most conspicuous example of a tilted surface is the western slope of the Sierra Nevada of California, which has been described by Whitney,[1] Diller,[2] Gilbert,[3] and others. It is, however, not a simple peneplain and its streams are not simple consequents combined with an older system of adjusted rivers, because lava flows have modified both. A smaller example, in which the tilted peneplain and the combined drainage systems may be seen, is found in Ben Lomond ridge, which extends north from Santa Cruz, California, to a distance of some 15 miles, and rises 2,500 feet above the Pacific in a distance of 6 miles.[4]

The surface of a tilted slope is usually deeply gashed by consequent canyons. The interstream areas, however, may preserve the aspects of the older surface, whether it was a well-developed peneplain or a mature topography of greater relief. We search for those areas and then proceed to question them as to their identity, their more or less intimate association with rock structures, and other suspicious relations. If they are not too much wasted by recent erosion they will bear positive testimony to their former state.

A form which is rarely, if ever, produced by differential erosion, is a long curve extending from valley to summit and *convex upward.* It may appear in transverse or in longitudinal section, and commonly in both, if at all. One inference is that it is a denuded anticline, which has been stripped down to a resistant bed and is an exposed fold in sedimentary rocks. But that guess gives way at once where such profiles are shown by hills of metamorphic and intrusive rocks, as is the case in the Coast Range of California. That range is traversed by great faults, which exhibit effects of very powerful compressive stresses and of greater horizontal than vertical displacements. The mountains adjacent to these faults are bowed up in consequence of internal shearing and the older topographic surface arches over them in an anticlinal form.

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[1] Whitney, J. D., Auriferous Gravels, of the Sierra Nevada, Harvard Coll. Mus. Comp. Zoo. *Memoirs,* vol. 6, pp. 63–64, 1880.

[2] Diller, J. S., Tertiary Revolution in the Topography of the Pacific Coast. U. S. Geol. Surv., *Fourteenth Annual Report,* pp. 408–410, 1892–93.

[3] Gilbert, G. K., *Science,* vol. I, p. 195, 1883.

[4] Santa Cruz atlas sheet, California, U. S. Geol. Surv.

Thus from our vantage point on a summit, at the end of a traverse which has enabled us to locate certain facts in their proper relations, we cross-question the landscape and from its responses to various questions we obtain some idea of the structures within our view and of the relative activity of erosion as compared with that of warping, folding, or faulting.

There is one test question which every feature of a landscape should answer: *Do you fit into the modern scheme of landscape sculpture? If not, why not?*

If we have lingered on our vantage point until the shadows lengthen toward the east, as it is wise to do, the run to camp will be made without further observation of geology, except perhaps of a locality to be visited on the morrow. Supper and the pleasant inertness that encourages smoking follow. It is not a time favorable to constructive thinking, but it is well to chew the cud of reflection in preparation for early morning thoughts. So supplied, the mind works while we sleep and presents us on waking with new suggestions, sometimes with the solution of a problem that has been particularly baffling the evening before.

The point I wish to make in this stage of the description of field methods is that thinking is appropriate to field work. Facts are to be scrutinized and classified. Gaps in the chain of facts are to be discovered and noted, that they may be filled when opportunity occurs. Groups of facts are to be examined as to their meaning and are to be placed in relation to one another as elements of an hypothesis. Hypotheses that will explain all the known facts and suggest lines of investigation are to be thought out.

Physiography takes first place in preliminary studies of structure because its facts are so large and so widely displayed. But we must turn to stratigraphy for the facts that enable us to interpret structure with an understanding of details. In an unknown field the immediate obligation is to ascertain the normal sequence in which the strata were laid down.

The primary condition of observation of strata is that they shall be exposed and the second is that the exposures shall succeed one another across the strike with as few gaps as possible. Different types of country offer very unlike opportunities and no rule can be laid down, but the geologist may save time by reasoning from the obvious topographic facts. A deep mantle of residual soil is avoided in a region of rejuvenated mountains by following the young canyons. Alluvium in an aggraded valley may drive one to follow the ridge tops. The windward side of a hill, as indicated by the lean of the trees, is more apt to show outcrops than the lee side, in an arid or semi-arid country. Glaciation may have buried everything except occasional rocks, for which one must make a systematic hunt. Whatever the conditions of accumulation of soil, it will somewhere have failed to cover the strata, and an intelligent analysis of the processes that have been at work will promote the discovery of the localities where the desired information can be obtained.

Measuring the thickness of strata is a question of gross measurement or of detail. For gross approximations, I resort to the paced traverse and plotted field map, which gives the observer complete freedom of movement from outcrop to outcrop, yet furnishes constantly the opportunity to ascertain at any moment what the observed section is. There is a very great advantage in instantaneous results over those which are postponed to some future time, when instrumental or written notes can be worked up.

Detailed studies for thicknesses and sequence are usually so related to requirements of precision that no pains will be spared to get accurate and connected results. A paleontologist friend, who measures as he collects, carries a 5-foot stick which he lays across the beds. Adding up items of thickness and correlating them with fossils, he knows at the end of a day's work the magnitude and the ages of the formations he has been over. Having adjacent sections in mind, he can compare, can infer the thickening or thinning of strata, may be directed to a concealed unconformity or fault, and always has at hand a mass of facts that make him a disconcerting opponent in debate.

Where strata are nearly horizontal, the factor of elevation of outcrop becomes more important than that of horizontal distance. We may then disregard the latter and draw a profile on which outcrops are placed according to their altitudes, as determined by repeatedly sighting on a level and multiplying by the height of eye, or by taking slope angles and paced distances, or by aneroid with proper checks. The variety of possible methods for getting the thicknesses of strata is great, and the main thing in field work is to know which to choose and how to pass from one method to another to secure the maximum efficiency.

Observations of thickness and sequence are simply means to an end, facts from which to infer the past history of the mountain region, including that of its structure. One of the most important distinctions is that between marine and continental deposits. The lines of inference as regards the structures are markedly different in the two cases. In marine beds, thicknesses are generally uniform or vary gradually. The succession of strata is apt to be the same over wide areas. It is possible to establish standard sections and to reason from their general continuity that discontinuity is to be explained by some peculiarity of structure, such as a fault. Alternatives are to be considered, of course, such as a disconformity, due to marine scour, or an actual uncomformity. But the probability that the original sequence of strata was invariable over large areas simplifies the study of the structural problem.

It is otherwise with continental deposits. They are characteristically lenticular and variable. The conglomerates are most so, the sandstones less so than the conglomerates, the shales least of the three. Correlations are therefore more certain when made on shales than on sands and surer on sands than on conglomerates. Yet the monotony of shales and their prevalence in many sections reduces their value as lithologic markers. In drilll logs sands are most often the basis of correlation, and their tendency to lenticular distribution as bars or in alluvial cones or as æolian deposits is the cause of much uncertainty. The surface on which continental formations are laid down is also less regular than that on which marine sediments accumulate, and the inequalities sometimes result in contacts that look like displacements. A Pliocene conglomerate in contact with a nearly vertical face of Miocene shale has been mapped in California as a normal fault in an oil field. It is simply one wall of an aggraded canyon of erosion in the shale.

Thus it becomes important to distinguish marine stratigraphy from continental, very much as we differentiate algebra from calculus, and to recognize the very much greater difficulty of stratigraphic and structural work in the latter class of deposits. The matter has assumed importance because continental formations are common in many oil fields.

The stratigraphic sequence underlies all interpretations of structure, just as spelling is the basis of intelligible writing, and the first task of the geologist in an unknown region is to ascertain it. More often than not in my experience the study of the structure has of necessity been carried on concurrently with that of the succession of strata and consequently with an element of uncertainty. The degree of difficulty varies very greatly. In some districts, as in the Paleozoic of New York where the standard sections for America have been established, the formations lie in regular order, unequivocally right side up and as they were deposited. There the succession of organic forms may be determined and, although there may be gaps in the record, we need never doubt but that we observe the true sequence as we pass from that which lies below to that which overlies, from older to younger.

It is otherwise where formations are overthrust or overfolded. We can no longer be sure, in the absence of fossils, which is truly upper or lower among the strata, and our structure remains capable of more than one interpretation. The complexity increases with the occurrence of intrusions and with metamorphism. It may then take years of patient research to unravel the tangled skein.

The field investigation of intricate structures must utilize the several methods of attack which have been outlined, together with all the aids of paleontology and petrography which the conditions may permit. Even in simple structures these give invaluable checks on inferences based on observations of the attitudes and sequences of strata, and in more complex studies they become essential.

It is not within the compass of this work to enumerate details of elaborate researches, such as have been found necessary to the solution of problems of Highland structure or of the Pre-Cambrian. For an understanding of their complexity reference should be made to the works of Peach and Horne, in the one case, and to those of Van Hise and his associates in the other.

One of the most puzzling examples of all structural geology is that which is presented by the Alps. Among the great contributions to geology which have resulted from a hundred years of study, the works of Albert Heim stand out significantly, as presenting most graphically the facts of structure, divested of theory. The peculiarity of Alpine structure lies in the association of enormous overturned folds with major and minor thrusts of great complexity. The currently accepted solution leads to mechanical impossibilities and will no doubt be modified eventually until it conforms to those principles which govern the transmission of stresses and the deformation of rock masses under terrestrial conditions.

The discussion of general surveys has been treated in detail because the methods involved are to a large degree applicable also to reconnoissance and special surveys.

Special surveys are those which have for their object some special phase of the geology, rather than a comprehensive mapping of all the features. They are generally commercial in character, and most problems of economic geology involving structural geology call for this class of work.

A special survey, as the name implies, requires some special knowledge on the part of the geologist; that is, he must be a specialist in the phase of the subject covered by the problem. For this reason the danger lies not in overlooking details, but in concentrating on them to the detriment of the broader phases of the problem. Just as the position of major structures may be indicated by those observed in a hand specimen, so are the minor structures, of economic importance, controlled by the general nature of deformation in the region in question. The student of ores, endeavoring to solve the problem of the fault system of a mine, must know whether the region be one of compression or of extension, and he must also know the direction of the compression, or the trend of the normal faults. The geologist hunting for oil structures will not find competent anticlines in a plateau region marked by monoclinal flexures and normal faults. Thus the specialist must to some extent share in the comprehensive knowledge of the explorer, and reason from the larger features of a region down to the details which are necessary to the solution of his special problem.

We cannot better conclude this outline of suggestions for field studies than by reiterating the recommendation to constantly frame explanations of observed facts, to systematically group the tentative explanations into hypotheses which must be consistent with mechanical principles, and to submit each hypothesis to the test of new facts, that are intelligently and intentionally sought out as critical proofs of falsity or truth.

The method of multiple hypotheses should be consciously and conscientiously adopted.[1] The difficulty with which this is attended is a good test of a man's fairness in scientific thought.

Scientific method consists in arranging known and related facts according to a definite idea, which shall explain them all consistently. The idea becomes an hypothesis which, like a new acquaintance, we naturally desire to cultivate. Having taken form in our own mind, it is a congenial acquaintance and soon becomes a friend. If permitted, it will become more than a friend and will rob us of our freedom of thought. Most thinkers are sooner or later thus robbed and too often by ideas that are only half true.

Safety lies in numbers. Having framed the first theoretical organism and considered its possibilities, dissect it again, lay the individual parts out, stripped to the bone, and reassemble them to form a different skeleton. It will become a competing hypothesis. Repeat the process. Develop genera, species, and varieties of hypotheses and let the law of the survival of the fittest have unrestricted play among them. Thus, and only thus, can you retain freedom to think according to the facts of Nature rather than according to your own notions.

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[1] Chamberlin, T. C., The Method of Multiple Working Hypotheses. *Jour. Geol.*, vol. V, pp. 837–848, 1897.

A great geologist said to me recently: "For more than 25 years I have consistently pursued the method of multiple hypotheses. One hypothesis, and one only, has met all tests that I could devise. Am I justified in adopting that hypothesis as true?" It is safe to say that the habit of thinking and questioning and thinking further, which has characterized this great philosopher, will always keep him in touch with Truth.

Our field hypotheses are necessarily crude and undeveloped. Nevertheless, they should be cordially entertained and encouraged to multiply, for they have the great advantage over later ideas that they are organized with fresh facts. It is an essential element of good field work that we should develop hypothetical explanations of that which we observe, and observation, coordination, and interpretation should go on constantly.

CHAPTER XIV

GRAPHIC METHODS AND PRACTICAL PROBLEMS

Strike and dip: bedding planes, determination of strike and dip. Determination of thickness of strata. Descriptive geometry: principles of normal projection, abbreviations and conventions, practical problems. Isometric projection. Graphic representation of geologic data: topographic maps, areal geologic maps; structure maps, structure shown by dip and strike, by structure contours; convergence maps; cross-sections.

STRIKE AND DIP

Definition.—The *strike* of a stratum is the bearing of a horizontal trace on the bedding plane. It is measured in degrees from north to east or west, and is designated by this measurement, as: north 60° west, or north 27° east. These are abbreviated as follows: N. 60° W., N. 27° E. Although the strike has two directions, for instance, northeast or southwest, the convention is always to designate it from north.

The *dip* of a stratum is the angle between a bedding plane and the horizontal, measured in a plane at right angles to the strike. Like the strike it is designated in degrees. For a given strike there are two possible directions of dip. For instance, if the strike is northeast the dip may be southeast or northwest. For this reason it is necessary to follow the statement of amount of dip by a statement of direction, as: 30° northeast, or 45° southwest. These are abbreviated to 30° NE. and 45° SW.

The combination of strike and dip defines the exact attitude of the stratum. An *observation* includes these two, and would appear in the notebook with the description of the formation, as follows:

A.T.P.[1] Str. N. 80° E. Dip. 25° SE.

---

[1] Abbreviation for "at this point."

Bedding Planes.—The strike and dip are measured on a *bedding plane.* A bedding plane is the plane which divides two adjacent strata or beds. The recognition of a bedding plane is of importance if an accurate observation is to be taken. The true bedding is often obscure and apt to be confused with jointing. The criteria stated below indicate the characteristics of each.

Bedding planes appear as planes of parting, or lines of weakness. The rock is apt to be weathered or stained along these lines. In this respect they are similar to joints. They are more regular, however, and, as a rule, do not show openings due to displacement, or rough surfaces except where those are caused by original conditions, such as the development of ripple marks.

In general, bedding planes are more continuous than joints. Except in the case of cross bedding or false bedding, they are usually parallel, as nearly as can be judged by eye, with little variation except when sharply folded. Joints are more apt to diverge from strict parallelism, even in extensive and uniform sets.

A sure mark of a bedding plane is a change in the nature of the material on the two sides.

The spacing of bedding planes varies, according to the material, from small fractions of an inch in finely laminated shale to many feet in heavy-bedded sandstones and limestones. The same is true of jointing, except that it rarely occurs very closely spaced in true sedimentary rocks. In slates, however, the cleavage, which is closely spaced jointing, has the appearance of thin bedding.

Certain marks are characteristic of bedding planes. Among these are ripple marks, rain prints, animal and mollusc trails, layers of shells, and other less common marks.

Ripple marks form a series of corrugations and ridges on the surface of the bed. They may be used not only to identify the surface, but to determine which is the upper and which the lower surface. In the normal ripple marks, the ridges are sharp and narrow, the hollows between are wider and smoothly concave, although sometimes there is a minor series of ridges in the middle of the hollow. In the cast of the ripple marks on the under side of the bed above, the reverse is true.

Rain prints are found on the surfaces of sandstone beds, sometimes on finer material, and consist of small round depressions dotting the surface.

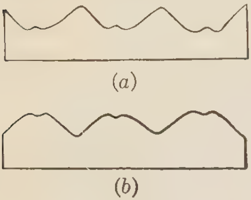


FIG. 125.—*a*. Profile of ripple marks. *b*. Profile of cast of ripple marks. (Modified after a photograph by Van Hise.)

Animal tracks, fossils, and other criteria are found under special conditions. In case of any doubt as to the direction of bedding, all available means should be used to determine the true direction.

Determination of Strike. — There are three methods of finding the strike of a bedding plane with the Brunton or Gurley compass.

In the first method a smooth surface on the bed, long enough to set the compass on, is necessary. Hold the edge of the compass parallel to the north-south line against the plane, and level the compass. The edge is then in contact with a horizontal line in the bedding plane, and therefore it has the direction of the strike. Read the compass bearing off the needle. (Fig. 126.)

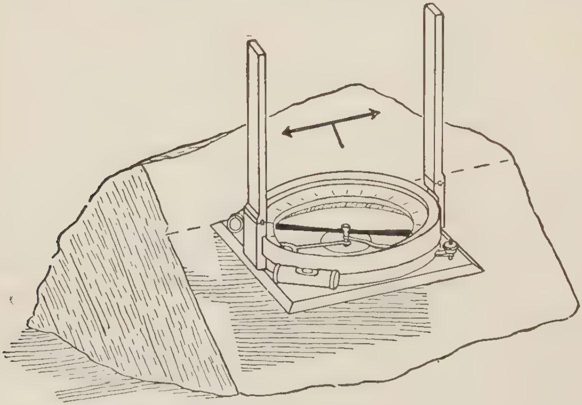


FIG. 126.—Taking the strike. Hold the compass level, as shown, and read the needle.

If the bedding plane is too rough, or a smooth portion of one plane large enough to take the edge of the compass cannot be obtained, stand away from the outcrop, choose a prominent bedding plane, and place the eye in the extension of the plane so chosen. Determine the point in the plane at the level of the eye, and sight the compass at this point, as in taking a bearing for a traverse. This direction corresponds with that of the strike.

The second method is more accurate for steep inclinations. In flat-lying beds it is difficult to judge the level line, and a small vertical difference makes a large error in the direction of the strike. This method can be used on outcrops which cannot be reached by other methods.

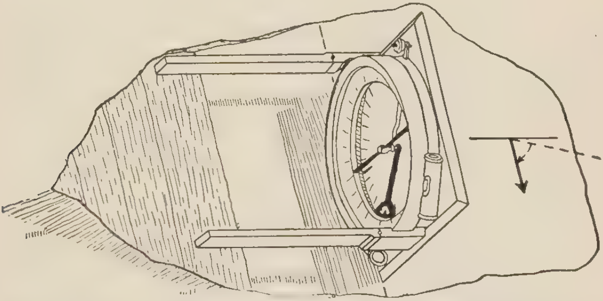


FIG. 127.—Taking the dip. Hold the compass vertical as shown, and read the pendulum or clinometer.

The third method is useful in flat beds where the exact horizontal line is difficult to determine. Clean off a surface as large as the base of the compass. Lay the compass flat on this surface and turn it until one of the bubbles reads level. The line of the axis of this bubble is the direction of strike, and this line can be marked, the compass re-oriented on it to give its bearing, and the needle read as above.

Determination of Dip.—To determine the dip of a bed, if the bedding plane offers a smooth and sufficiently large surface, place the edge of the compass parallel to the north-south direction against the plane, with the compass in a vertical position, at right angles to the strike, and read the clinometer. If the compass is a

Brunton, the vertical bubble must first be leveled. In the Gurley compass the clinometer consists of a pendulum. This must swing free before being read. (Fig. 127.)

If the bedding plane does not offer a smooth surface, stand away from the bed, sight along the strike as in taking the strike, hold the compass vertically so that the edge parallel to the north-south line lies in the line of sight and is parallel to the bedding plane, and read the clinometer as in the first case.

Record the results immediately in the notebook.

THICKNESS OF STRATA

It is often necessary to find the approximate thickness of strata, without the use of a tape or stick measuring directly across the beds. Such is the case when strata are crossed by a pacing traverse, outcrops located and dips taken, but no accurate measurement made. Two cases arise, namely when the strata are parallel, and when they are folded.

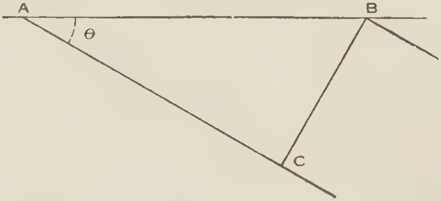


FIG. 128.—Thickness, outcrop width, and dip of strata. Parallel dips and strikes.

Strata with Uniform Strike and Dip.—In Fig. 128 it is obvious that there are three factors entering into the problem, the distance AB, or outcrop width, the dip, θ, and the thickness BC. If any two are given, the other one may be found, either graphically, or by trigonometry.

For instance, if the outcrop width AB, and the dip θ are given, the thickness can be found by laying off AB, drawing the dip θ at A, and dropping a perpendicular from B to the line of dip at C. BC

is the thickness. In the triangle ABC, $BC/AB = \sin \theta$. Hence $BC = AB \sin \theta$. By means of the same equation either the dip or the outcrop width can be found if the other two factors are known.

If A and B are not at the same elevation, however, a fourth factor is introduced, the difference of elevation, BD (Fig. 129). If this is known, the problem may be solved as above, care being taken, however, to measure the angle of dip from the horizontal, and not from the line connecting A and B. The tangent of the angle α is BD/AD, and $AB = BD/\sin \alpha$. The thickness $BC = AB \sin (\theta + \alpha)$. (Fig. 105.)

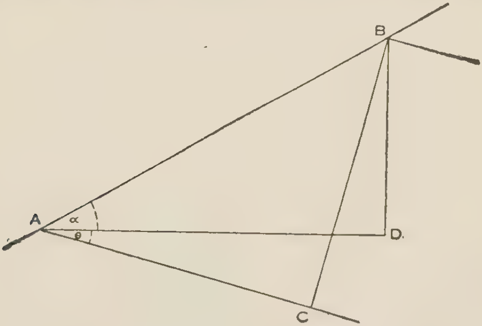


FIG. 129.—Thickness of strata with varying elevation.

Strata with Divergent Dips.—In Fig. 130 are shown two outcrops with parallel strikes, but with dips of unequal magnitudes. The simple solution possible in the preceding case cannot be applied here. In fact, unless certain ideal conditions are assumed, no solution is possible. The ideal condition assumed is that the fold of the beds between these two points corresponds to the arc of a circle. The solution is indicated in Fig. 130 as follows: The dips are plotted in a section normal to the strike. Perpendiculars are drawn to the dip lines at the points of outcrop. If the dips are not parallel these perpendiculars must intersect, either below the outcrops, as in Fig. 130a, or above, as in Fig. 130b, This point of intersection, C, is then used as the center of an arc, swung from the nearer point of outcrop, A, and intersecting the perpendicular from the farther point *B* at *D*. *BD* is the thickness of the strata between *A* and *B*.

The limitations of this method are that the folding must be of the concentric type, and that only one limb of the fold can be measured at a time. The closer together the observations the more accurate it becomes, and it fails altogether if there is any considerable change in the curvature of the strata between the two outcrops. Nevertheless, the degree of accuracy that can be obtained with it under normal conditions is amazing.

This method of swinging arcs can be used to considerable advantage in constructing cross-sections of open folds. In any case, however, its limitations must be kept in mind, and judgment exercised in its use.

If the strikes are not parallel, the same method can be used in a few cases to determine the outcrop width, the perpendiculars being drawn from the points of outcrop perpendicular to the strikes, but this is not as generally applicable as the method of finding the thickness.

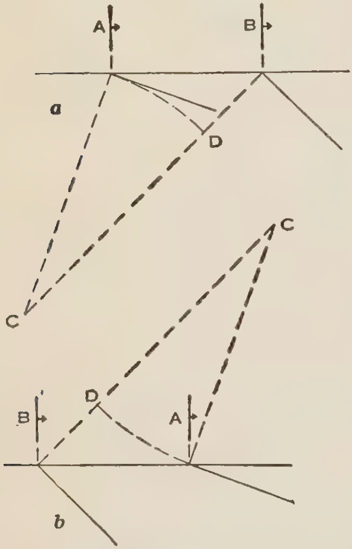


FIG. 130.—Thickness of strata, divergent dips.

DESCRIPTIVE GEOMETRY

Descriptive geometry is a method of representing on a plane surface objects which have three dimensions in space. It also offers a means for the graphic solution of problems involving three dimensions. As nearly all problems of structural geology are of this nature, a knowledge of the principles of descriptive geometry is essential to the structural geologist.

There are several divisions of descriptive geometry. Only two of these will be considered here, the two which have the most immediate and practical bearing on geologic problems.

The first of these is called *normal projection,* and involves the projection of objects on two or more planes, at right angles to each other. This is the most useful method for the solution of most geologic problems. Map and section fall under this head. Its drawback is that it does not give the space relations of all three dimensions in one picture, but requires two or more pictures or "projections" to accomplish this.

The other division is called *isometric projection* and involves the projection of objects on a plane inclined to the three major directions and giving a single image showing the three dimensions. In the solution of problems in which the lines or figures considered lie in three planes mutually perpendicular, this method is very desirable. In problems in which the elements are not directly related to three such planes, normal projection is more convenient. Isometric projection, however, is the more useful for purposes of illustration. It has been used for that purpose in this book, therefore an understanding of its principles is desirable, and a brief account is included.

Projection.—The projection of a point on a plane is a point. It is that point at which a line having a given direction and drawn through the original point pierces the plane. The plane is called the *plane of projection,* the direction of the line is called the *direction of projection.*

The same definition can be applied to the projection of a line, a plane, or a solid. In any one projection the direction of projection remains constant.

Normal Projection.—If not otherwise stated, it is assumed that the direction of projection is perpendicular to the plane of projection. This is called normal projection.

Projection on Two Planes.—If the projections of a point on two known planes is known, the position of the point is fixed, provided the two planes are not parallel. (Fig. 131.)

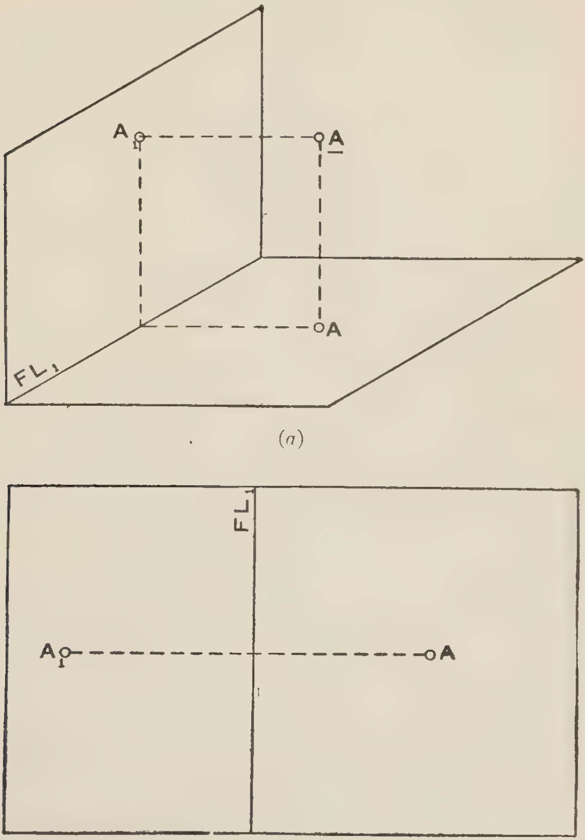
The line of intersection of one plane with another is called the *trace* of that plane on the other.

The trace of one plane of projection on another is called the *folding line.* In normal projection the angle made by two adjacent planes of projection (those having a common folding line) is always a right angle.

In case the contrary is not stated, the first plane of projection is horizontal and is assumed to be in the plane of the paper. This is called the *horizontal projection, plan,* or *map.* Any adjacent plane of projection must therefore be vertical in normal projection. This is the *vertical projection, elevation,* or *section.* Plan and elevation are the terms used in architecture, map and section are those used in geology.

To represent both projections on a flat piece of paper, the vertical plane is rotated about the folding line as an axis, into the plane of the paper. This involves a rotation of 90 degrees. There are two methods of performing this rotation. If the object to be drawn is placed above the horizontal plane and to the right of the vertical plane, the vertical plane is rotated away from the object, as in Figs. 131 and 132. The effect of this is to put the highest point in the vertical projection farthest from the folding line. Thus, in Fig. 132, a is higher than b, hence a'' is further from the folding line than b''. In geological work, as well as in other sciences using descriptive geometry, it is desirable to have the higher points nearer the folding line. For instance, a geologic section is generally drawn below the line of section on the map. Considering this line of section as a folding line, it is obvious that the top of the section, the profile of the surface, is next to the folding line. This result is accomplished in descriptive geometry by placing the object under the horizontal plane and to the left of the vertical plane, projecting it upward and to the right. The vertical plane is then rotated away from the object as before, but the object appears with its upper points nearest the folding line, as desired. (Fig. 133.) Point A is above point B, and A_2 is nearer the folding line than B_2. This is called *third quadrant projection,* because the object is placed in the third quadrant.

The method illustrated by Figs. 132 and 133 is known as first quadrant projection. Except in Problem 1, where first quadrant is used for better illustration, third quadrant projection has been used throughout this chapter.



(a)

(b)

FIG. 131.—Normal projection. *a.* Projection onto two planes at right angles to each other. *b.* The same planes rotated into the plane of the drawing.

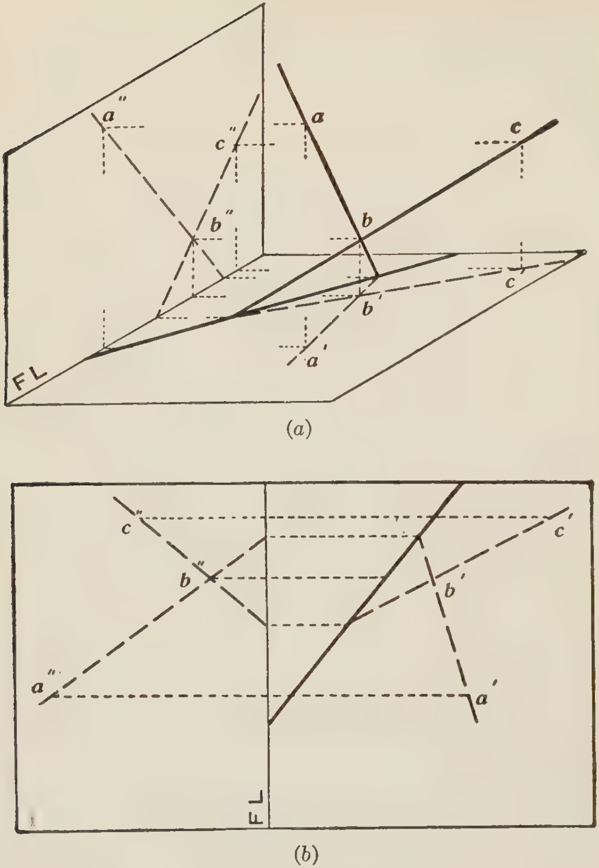
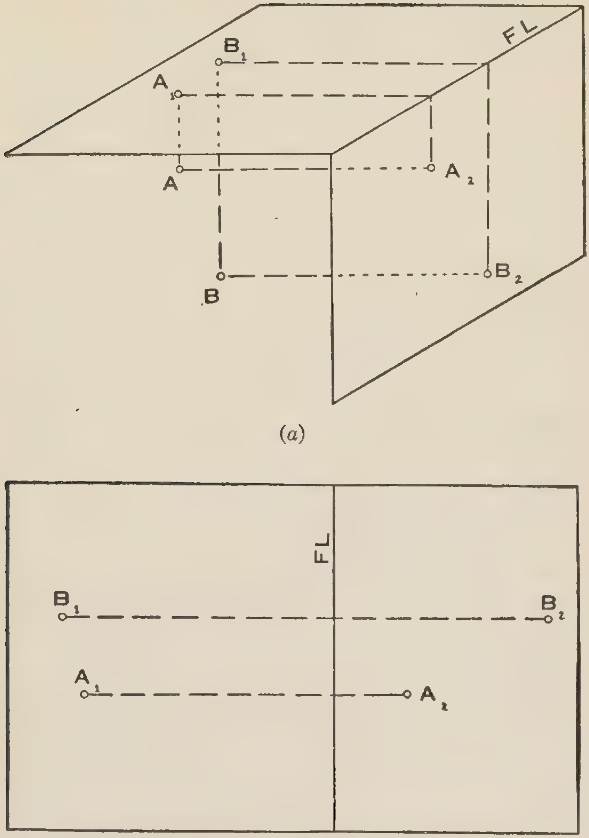


FIG. 132.—Normal projection in the first quadrant. *a.* The projection of two lines and their intersection on two planes at right angles to each other. The heavy line in the horizontal plane represents the trace of the plane defined by the two lines on the horizontal plane. *b.* The same, as it would appear after rotation of the vertical plane into the plane of the paper.

A plane of projection does not have to be either horizontal or vertical. If a folding line is taken between the vertical projection and some other plane, and if this folding line is not parallel or perpendicular to that between the horizontal and vertical planes, the third plane will be oblique to both these directions.



(a)

(b)

Fig. 133.—Normal projection in the third quadrant. *a.* Position of planes and object before rotation of the vertical plane. *b.* Position after rotation.

In geology the terms *strike* and *dip* are used to describe the attitude of a plane. The strike of a plane defined, in terms of descriptive geometry, is the direction of its trace on the horizontal projection. The dip is the angle it makes with any horizontal plane, measured at right angles to the strike.

PRINCIPLES OF NORMAL PROJECTION

1. The line connecting the projections of a point on two adjacent planes of projection is perpendicular to the folding line. (See Fig. 131.)

2. The vertical projection of a point is as high above the folding line as the point is above the horizontal plane. This is true for all possible vertical planes on which the point may be projected. Hence the height of any two vertical projections of a point above the folding lines between their planes and the horizontal is the same.

This principle may be stated more generally as follows:

In any two planes of projection adjacent to the same plane the distances of the projections of a point to the respective folding lines between these planes and the common plane will be equal.

The two preceding principles enable us to take a folding line in any direction whatever, and to locate the vertical projection of a point in the corresponding plane, provided the horizontal projection and any one vertical projection of the point are given. This holds true likewise for any three adjacent planes of projection.

ABBREVIATIONS AND CONVENTIONS

In the problems in this book the following abbreviations and conventions will be followed:

Points will be designated by capital letters, as: A, M.

Lines will be designated by their terminal points, as: AB, MN.

Planes other than projection planes will be designated by underlined capitals, as: $\underline{A}$, $\underline{F}$, $\underline{P}$.

Areas in planes will be designated by the points on their boundaries, as: *ABCD*, *MNP*.

Angles will be designated by small letters, as: *a*, *b*, *c*.

Planes of projection will be designated as follows: the horizontal projection will be called *H*. All points in it will be given a letter without a qualifying number. All vertical planes will be called sections, and numbered in order. The folding line between them and the horizontal will be designated *FL* and given the same number, as FL_1 between *H* and Section 1. If a plane is taken which is not a section, it will be numbered in turn and its folding line likewise. Any projections except those on *H* will carry the original letter, qualified by the number of the section or projection plane, as A_1, B_3.

PRACTICAL PROBLEMS

The following problems are introduced to show the method of normal projection and its application to the solution of problems arising in structural geology:

Prob. 1. Fig. 134.

Given: Two projections of a point, *A* and A_1, and a second folding line, FL_2.

To find: The third projection of *A*.

Solution:

Let the point where the line between *A* and A_1 cuts FL_1 be designated by *B*.

From *A* draw a perpendicular to FL_2 cutting it at *C*.

On the extension of *AC* through *C* lay off a distance equal to *AB*. The point thus located is the desired point, A_2.

Prob. 2. To find the true length of a line. Fig. 135.

Given: Two projections of a line, *AB* and A_1B_1. To find the true length of *AB*.

Solution:

Take FL_2 parallel to AB.
Find A_2B_2 by the method of Problem 1.

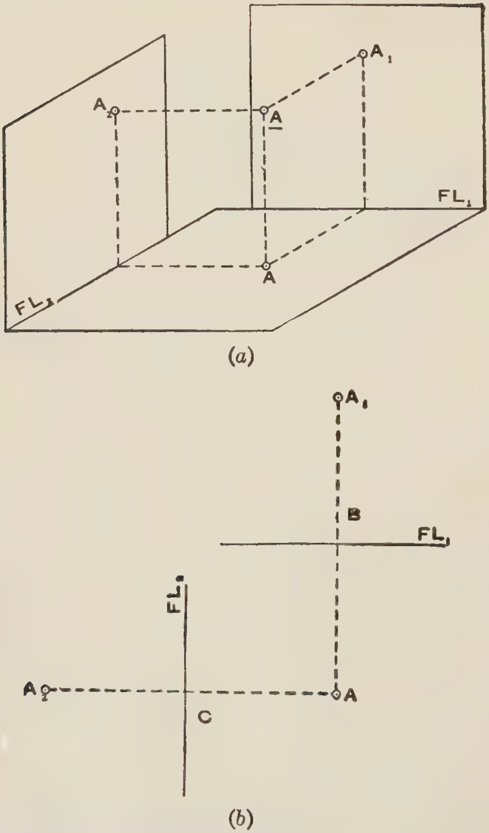


FIG. 134.—To locate the third projection of a point. *a.* View of the three projection planes before rotation. *b.* Solution of the problem.

A_2B_2 is the true length of AB, because the third plane of projection is parallel to the line in space, hence the projection of the line on it must have the same length as the line itself.

PROB. 3. To find the dip and strike of a plane. Fig. 136.

Given: Three points, A, B, and C, in a plane, and the elevation of each.

To find: The strike and dip of the plane.

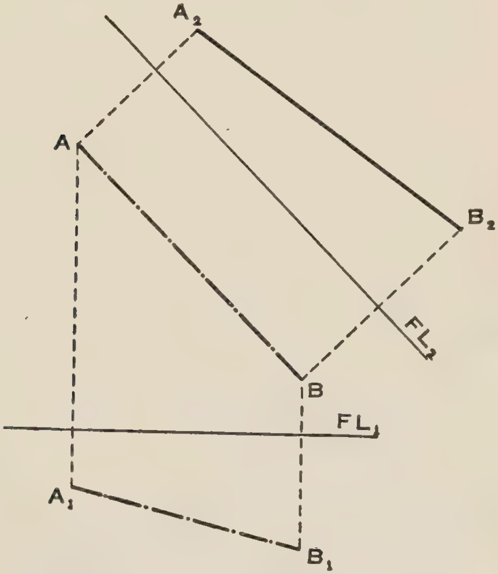


FIG. 135.—To find the true length of a line.

Solution:

Take FL_1 in any convenient position. Locate A_1, B_1, and C_1 by means of projection and their comparative elevations.

Draw a horizontal line through C_1 cutting A_1B_1 at D_1.

Project D_1 back into H, locating D on AB.

Draw CD. The direction of CD is the strike of the plane, as it is a horizontal line in the plane, because C and D have the same elevation.

Take FL_2 perpendicular to the strike (to CD). Locate A_2, B_2, and C_2. These three points will lie in a line. The angle this line makes with the horizontal (FL_2) is the dip of the plane.

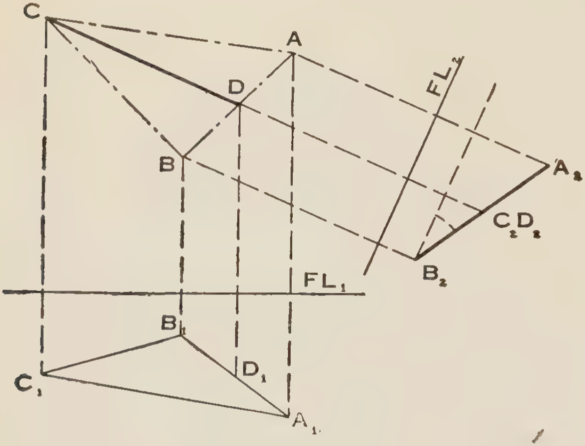


FIG. 136.—To find the dip and strike of a plane.

PROB. 4. To plot a dip in a section not at right angles to the strike. Fig. 137.

Given: Plane P with known strike, outcropping at A, and dip a; FL_1.

To Find: The trace of $\underline{P}$ on Section 2.

Graphic Solution:

Take FL_2 normal to the strike.

Plot the trace of $\underline{P}$ on Section 2 by means of A_2 and the dip a.

Draw a line at some convenient distance below FL_2, cutting the trace of P_1 and B_2.

Draw a line perpendicular to FL_2, from B_2 cutting it at C. Continue this line through C to cut FL_1 at D. This line is parallel to the strike (as FL_2 was assumed perpendicular to the strike) and may be considered as a contour on P at the assumed distance below the outcrop A.

From A extend the strike to cut FL_1 at A_1.

From D drop a perpendicular to FL_1 and locate B_1 at distance B_2C below D.

Draw A_1B_1. This is the trace of P on Section 1.

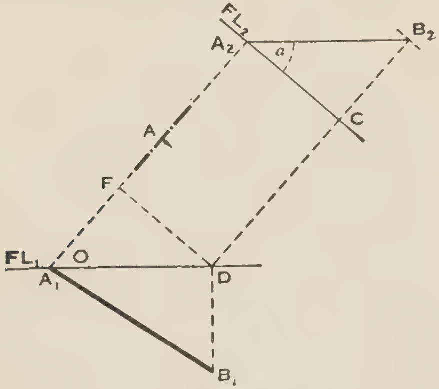


FIG. 137.—To find the apparent dip of a plane in a given section.

Trigonometric Solution. Let o represent the angle between the strike and FL_1.

Draw a line perpendicular to AA_1 cutting it at F. In the triangle A_2B_2C: the angle $A_2 = a$; the angle $C = 90$ degrees.

$$\text{Therefore: } A_2C = \frac{B_2C}{\tan a}.$$

In the triangle A_1DF: the angle $A_1 = 0$.

the angle $F = 90$ degrees.

$$DF = A_2C.$$

Therefore

$$A_1D = \frac{DF}{\sin o} = \frac{B_2C}{\sin o \tan a}.$$

In the triangle A_1B_1D: the angle $D = 90$ degrees. $B_1D = B_2C$.

Therefore:

$$\text{Tangent of angle } DA_1B_1 = \frac{B_1D}{A_1D}$$
$$= \frac{B_2C \sin o \tan a}{B_2C}$$
$$\text{Angle } DA_1B_1 = \sin o \tan a.$$

This angle is called the *apparent dip* in Section 1. It is of much importance in constructing sections showing geologic structure, when the section is not normal to the strike. Tables showing the value of this angle for varying values of a and o are called dip tables, and are constructed from the above formula. See Appendix I.

PROB. 5. To find the true shape of a figure. Fig. 138.

Given: Horizontal projection of area $ABCD$, and dip a and strike of the plane in which they lie.

To find: The true shape of $ABCD$.

Graphic Solution:

Take FL_1 normal to the strike.

Project A into section 1, assuming an elevation for A_1.

Draw a line through A_1 making an angle a with FL_1. This represents the trace of the plane on Section 1.

Locate by projection B_1, C_1 and D_1 on this line.

Take FL_2 between Section 1 and projection plane 2, parallel to $A_1B_1C_1D_1$. This makes projection plane 2 parallel to the plane of $ABCD$, hence the projection of the figure on it will be in its true shape.

Locate $A_2B_2C_2D_2$ by the method of Problem 1. This is the desired figure.

This problem has a practical application in determining the area of a vein bounded by faults or claim lines, when the dip and strike are known, in order to compute tonnages. It will be seen by inspection that the area $A_2B_2C_2D_2$ is equal to the area $ABCD$ divided by the cosine of the dip a.

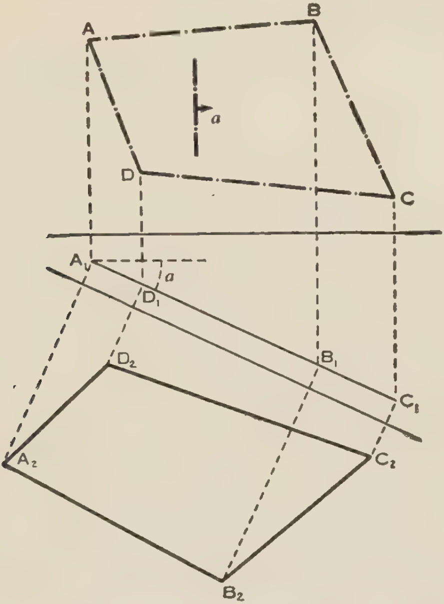


Fig. 138.—To find the true shape of a figure in a plane.

Prob. 6. To find the intersection of two planes. Fig. 139.

Given. Planes $\underline{A}$ and $\underline{B}$, $\underline{A}$ outcrops at A, with known strike and dip a, $\underline{B}$ outcrops at B with known strike, and dip b. The elevation of A and B are given.

To find: The intersection of $\underline{A}$ and $\underline{B}$.

Solution:

Take FL_1 normal to strike of $\underline{A}$ and FL_2 normal to strike of $\underline{B}$.

By projection, and their known elevations, plot A_1 and B_2

By means of the dips a and b, draw the traces of $\underline{A}$ and $\underline{B}$ on Sections 1 and 2 respectively.

In Section 1, locate a point C_1 on the trace of $\underline{A}$, having the same elevation as B. Locate D_1 on the same trace at a convenient elevation below C_1.

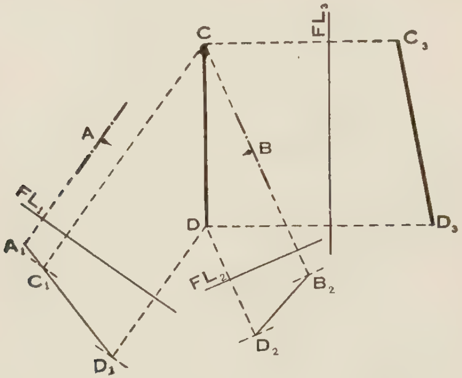


FIG. 139.—To find the intersection of two planes.

In Section 2, locate D_2 on the trace of $\underline{B}$ at the same elevation as D_1.

Project D_1 and D_2 back into $\underline{H}$, locating D at the intersection of the projection lines. Project C_1 back to intersect the strike line of $\underline{B}$ through B at C.

Draw CD. CD is the horizontal projection of the intersection of $\underline{A}$ and $\underline{B}$.

To find: the dip of the intersection of A and B:

Take FL_3 parallel to CD. Locate C_3 and D_3 as in Problem 1. The angle between C_3D_3 and FL_3 is the desired angle.

This problem is of importance in determining the areas of veins cut off by faults of known dip and strike.

PROB. 7. To find the direction and amount of displacement on a fault when the direction of movement and the offset portions of a vein are known. Fig. 140.

Given: Fault F, with dip o; vein A and its offset portion B, intersecting F at A and B, respectively, and both with dip a; and the direction of displacement on F, XY.

To find: The amount of displacement of F.

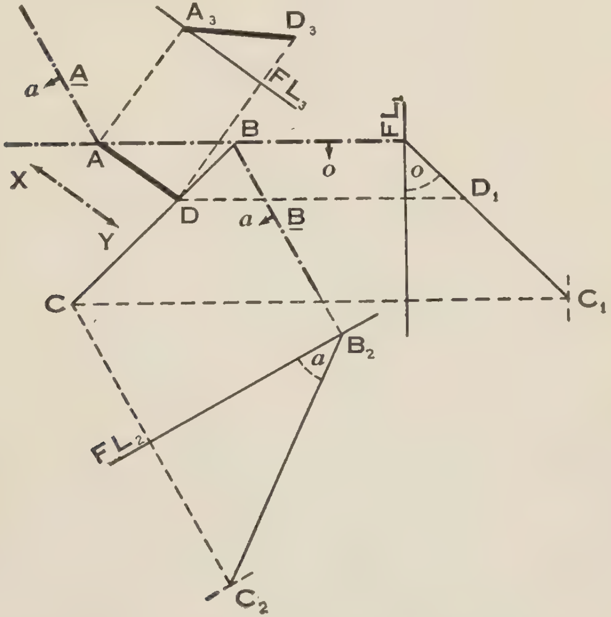


Fig. 140.—To find the displacement on a fault when the direction of movement and the offset of one vein is known.

Solution.

Take FL_1 normal to the strike of F, and FL_2 normal to the strike of B.

By the method of Prob. 6 find the intersection of F and B, BC.

From A draw a line parallel to XY, intersecting BC at D.

AD is the horizontal projection of the displacement on F:

Project D into Section 1, locating D_1 on the trace of F.

Take FL_3 parallel to AD, and locate A_3D_3 by projection and Section 1.

A_3D_3 is the amount of displacement on $\underline{F}$.

The practical value of this problem is evident. Many cases arise where a fault cuts off a vein, in which the offset portion of the vein can be located by the above method. By taking sections parallel to the fault, and to the vein, the various components of movement on $\underline{F}$ can be readily found.

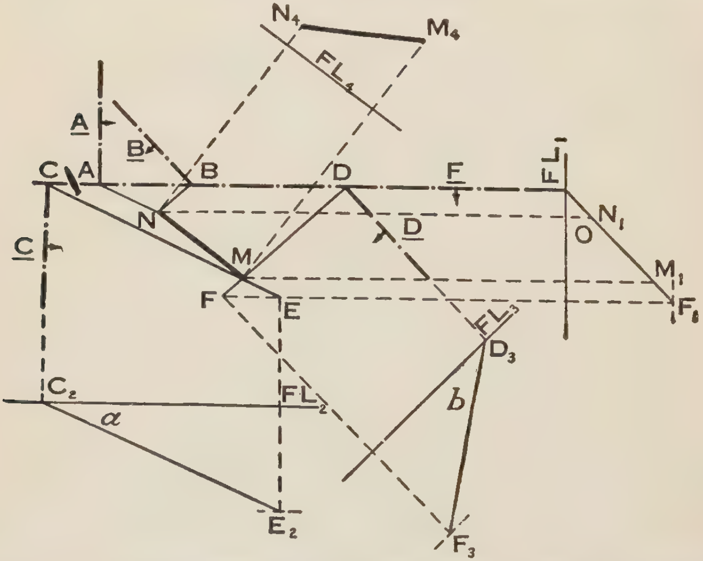


FIG. 141.—To find the displacement on a fault when the offset of two veins is known.

PROB. 8. To find the displacement on a fault when the offset portions of two veins are given. Fig. 141.

Given: Fault $\underline{F}$, with dip o; veins $\underline{A}$ and $\underline{B}$, with their offset portions $\underline{C}$ and $\underline{D}$, intersecting $\underline{F}$ at A, B, C and D respectively. $\underline{A}$ and $\underline{C}$ have a dip a, $\underline{B}$ and $\underline{D}$ a dip b.

To find: the direction and amount of displacement on $\underline{F}$.

Solution:

Take Folding Lines 1, 2 and 3 normal to $\underline{F}$, $\underline{C}$ and $\underline{D}$ respectively, and locate the intersections CE and DF of $\underline{C}$ and $\underline{D}$ with $\underline{F}$. Continue CE and DF to intersect in M.

Draw lines through A and B parallel to CE and DF respectively, intersecting in N. These represent the traces of $\underline{A}$ and $\underline{B}$ on $\underline{F}$.

Draw MN. MN is the horizontal projection of the displacement of $\underline{A}$ and $\underline{B}$ on $\underline{F}$.

Project M and N into Section 1, locating M_1 and N_1 on the trace of $\underline{F}$.

Take FL_4 parallel to MN and locate M_4 and N_4 by means of projection and measurements from Section 1.

M_4N_4 is the amount of displacement on $\underline{F}$.

As in the preceding example, the throw, heave, and shift can be determined by taking sections in the proper direction, or by direct measurement in the projections already drawn.

ISOMETRIC PROJECTION

Isometric projection has for its basis the cube. In the cube the bounding planes are considered to lie horizontal and vertical, the four vertical planes striking northeast and northwest. The cube is represented by a single projection in which the direction of projection is that of a line through the upper southern corner of the cube and the lower northern corner. This is a diagonal of the cube. The cube then appears as in Fig. 142, the dotted lines representing the concealed edges of the cube.

This figure is the starting point for all isometric drawings. Certain facts concerning it are apparent from inspection. The chief of these is that the lines radiating from the center, the edges of the cube, form angles of 120 degrees, the hidden edges being rotated 60 degrees from the position of those in front. All the edges are equally inclined to the plane of projection, hence they all appear of equal length in the projection. These facts make the cube very simple to construct.

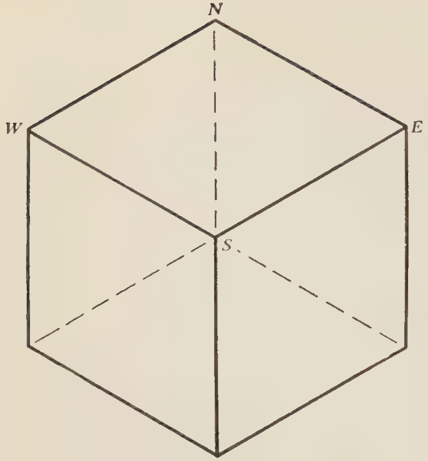


Fig. 142.—The isometric projection of a cube.

Figure 143 shows the method of measuring lines lying in one of the three planes of the cube. With *MO* as a diagonal, a square *MN′OP′* is constructed. This is equivalent to rotating *MNOP*, the upper plane of the cube, into a position parallel to the plane of projection. Hence any line or figure in this plane, which is rotated with it, will appear in its true length or shape after rotation.

Considering the line *OP*, its equivalent is *OP′*. As this line lies in one of the three major directions of the cube, all three of which have equal inclinations to the plane of projection, it will be seen that the ratio between *OP* and *OP′* is constant for any line in the projection parallel to one of these three directions. This ratio is called the *isometric ratio*, on which is constructed the *isometric scale.* Considering the line *MO*, it is seen that it is in its true length in the original projection. The line *NP*, however, extends to *N′P′*, which is a larger

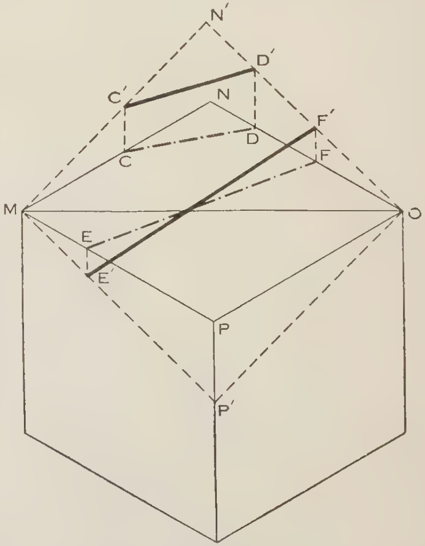
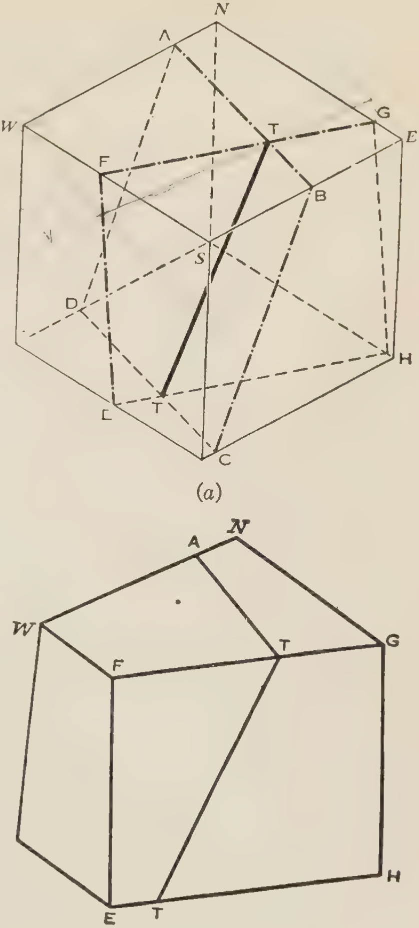


Fig. 143.—Measurement of lines in an isometric projection.

ratio than in the case of AB. Therefore we have in the plane $MNOP$ lines with all degrees of shortening, between none at all and the amount shown in NP. The method of finding the length of lines not corresponding to the isometric scale is shown by CD and EF. These two are first extended to cut the edge of the plane; then the point of intersection is projected perpendicular to MO, the axis of rotation, to the edge of the rotated plane.

In Figs. 144 *a* and *b* the method of locating the intersection of two planes is shown. Fig. 144 *a* shows the method of construction, with the hidden lines dotted in. Fig. 144 *b* shows the same figure, without the hidden lines, and with the front portion of the block cut away to one plane, as is done for purposes of illustration.

Some points in the construction may be noted. Where a plane cuts the cube, the trace of that plane on opposite sides of the cube must be parallel. Thus AB and CD are parallel, likewise AD and BC, FG and EH, and so on.



(*a*)

(*b*)

Fig. 144.—Isometric projection of the intersection of two planes. *a*. Construction. *b*. Result, with part of the cube cut away.

The strike of these two planes is found by rotating the upper plane of the cube, as in Fig. 143, and measuring the angle between AB or FG and the north-south line through the edges of the cube.

A great variety of problems can be solved by this method. As before stated, those problems the lines of which are parallel to the three major directions of the cube are the most easily solved. The aims of this volume however—brevity and simplicity—would both be defeated if any attempt were made to go into the details of such solutions.

One application of the isometric method deserves mention. It may be used to construct accurate relief drawings, to which sections may be added, from topographic maps. The map may be laid off in squares, corresponding to squares drawn in the isometric projection. Points on the map may be located in these squares, and elevations measured above a datum plane, these measurements being made by means of the isometric ratio. Outstanding points so located, valleys, hills, and junctions of streams, may then be connected to make the relief diagram.

GRAPHIC REPRESENTATION OF GEOLOGIC DATA

The facts of geology are usually illustrated by means of maps and cross-sections. As first observations are made at the surface the first stage in their study is their representation on a map. Four kinds of maps may be recognized, each of which is intended to show a different group of facts. The first is the topographic map. This does not include any information of a strictly geologic nature, but it is useful to the geologist and particularly to the structural geologist, as it reveals the relation of observed facts to the elevations. The second class of maps includes those which show the distribution of formations at the surface. These are called *areal* geologic maps. The third class shows structure. The fourth class includes all maps which are confined to special groups of facts, such as economic geologic maps and soil maps. They are usually areal or structural maps with certain features emphasized or others omitted.

Topographic Maps.—Topography is best shown either by contours or by shading. A *contour* is a line drawn on any surface through points of equal elevation. It is the intersection of a horizontal plane with the surface. Contours are drawn on the topographic surface in such a way that the planes in which they lie are equally spaced vertically. The vertical distance between contours is called the *contour interval.* By numbering contours with reference to their elevation above sea level the elevation of any point on a topographic contour map may be determined. This is of value in constructing cross-sections and in solving problems of structural geology.

Areal Geologic Maps.—Though such maps usually show other features, the principal information on them is the areal distribution of formations. The pattern of the *contacts* or lines of division between formations expresses facts of structure which the geologist must be able to read. Some of the facts which can be gleaned from them are as follows: In sedimentary rocks, the regional structure, whether horizontal, gently dipping, monoclinal, faulted, or folded is revealed at a glance. The character of the folds, whether symmetrical or unsymmetrical, the direction of the axial plunge, and the positions of anticlines and synclines, are apparent. Unconformity and overlap can be seen in many cases. If igneous rocks are present their age relations can often be determined. The contacts of igneous and sedimentary rocks show whether the latter overlie the former or have been intruded into them.

The study of areal maps, without recourse to cross-sections or to other types of information which may be plotted on them, is probably the most valuable exercise that the student of geologic structures can pursue, lacking the opportunity to observe relations in the field. It develops his sense of three dimensions and aids him in the solution of actual problems when he does encounter them on the ground.

Structure Maps.—Geologic structure may be shown on a map in various ways. The most useful are by means of symbols to show strike and dip, or by structure contours.

The position of any structure or rock mass which is tabular in form may be defined by its strike and dip. Bedding, joints, fault planes, cleavage, dikes, sills, and veins all fall in this class. Usually, however, strike and dip symbols refer to either bedding, faults, or veins. The usual symbol for strike and dip is a straight line in the direction of the former, with an arrow indicating the latter (Fig. 145). The amount of the dip is shown by figures, the direction of the strike is not recorded as the strike line is correctly oriented.

Combinations of dip and strike symbols indicate the various structures assumed by sedimentary rocks, such as folds and flexures. These may be added to by drawing lines on the axes of folds, or on other features which it may be important to define. This is the form of expression of structure usually employed in field work, as observations are made and plotted at the time, and it is only by the correlation of them, one with the other, that the structure can be interpreted.

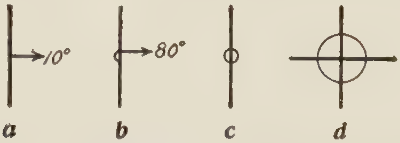


FIG. 145.—Strike and dip symbols: *a*, inclined beds; *b*, overturned beds; *c*, vertical beds; *d*, horizontal beds.

A more refined method of depicting structure is by *structure contours*. These are sometimes called *subsurface* contours, to distinguish them from topographic contours which are drawn on the surface of the ground. Structure contours are drawn on the surface of any single bed, and bear no relation to its outcrop or to the topography. They reveal the structure of the series of which the contoured bed is a member. This bed is called the *key bed*. As in the case of topographic contours, they show the elevation of the key bed relative to some horizontal datum plane, usually sea level. Examples of structure contours and the usual terms for the structures they may represent are shown in Fig. 146.

Structure mapping by means of contouring is carried on by

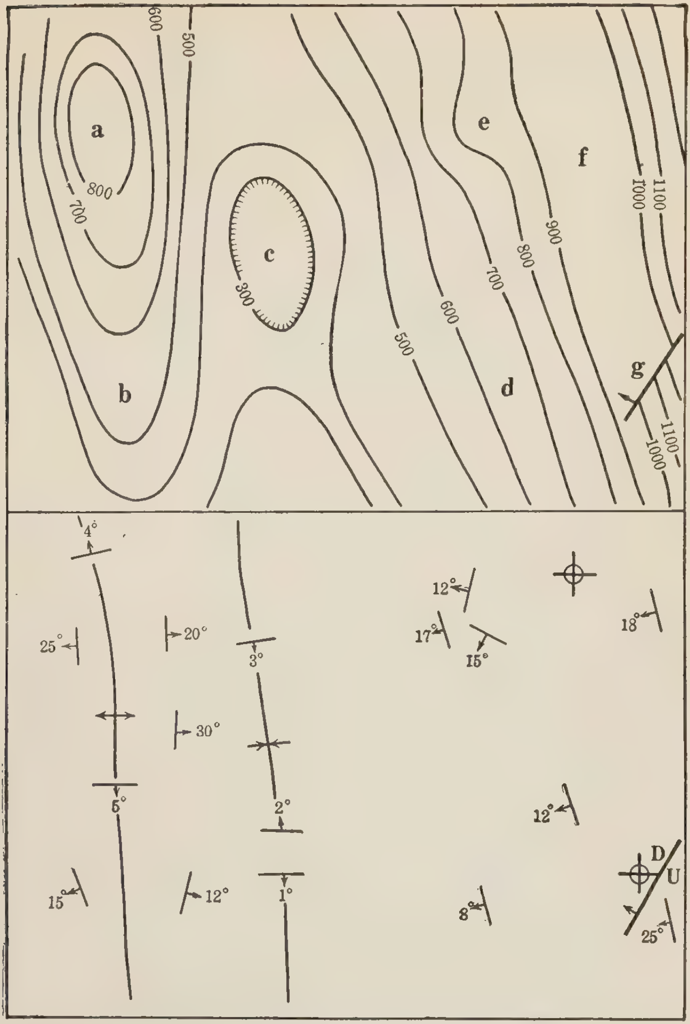


FIG. 146.—Methods of showing geologic structure of sedimentary beds.

Upper: Structure contours, giving types of structure and the names commonly applied to them in economic practice: *a*, closed anticline, dome, or closure; *b*, plunging anticline; *c*, closed syncline: *d*, monocline; *e*, nose; *f*, terrace; *g*, fault.

Lower: the same structure shown by strike and dip symbols.

the determination of the relative or actual elevation of points on the key bed. Contours are drawn between these to show the structure. The points may be determined in a variety of ways. Where the bed outcrops at the surface they may be taken along the line of its outcrop. Where it is eroded points may be determined on some other bed, the thickness of the beds between the two measured, and this thickness added or subtracted from the elevation of the second bed to determine that of the key bed. This is the method of surface mapping. Another method is by measurement of the depth to the key bed in wells. This, subtracted from the elevation of the ground at the well, gives the " datum " or elevation of the point on the key bed. Such work is known as *subsurface* work.

Occasionally it is necessary to determine the contours on a bed which is not exposed, when the thickness between it and the exposed beds varies. If this variation in thickness is fairly regular and can be determined at a few points, it is possible to do this by means of a *convergence map.*[1] Such a map shows the thickness between two beds, or the thickness of a given formation. Lines are drawn on it through points of equal thickness, in the same way that contours are drawn. By combining the data shown on it and on the contour map of the upper bed, any desired number of points on the lower bed may be determined and contours drawn from them. This is of great importance in oil geology, as the structures in the surface beds may be less pronounced than those in the subsurface beds, or a regional thickening of the formations above the oil-bearing strata may cause structures which are apparently closed in the surface beds to be open below, or vice versa. Fig. 147 shows a contour map on an upper bed, a convergence map, and the resulting contour map on the lower horizon. It illustrates well how much difference there may be between the first and the last, even though the variation in thickness of the beds is perfectly uniform in direction and amount.

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[1] Sometimes called an isopachous map, from the Greek meaning *equal thickness.*

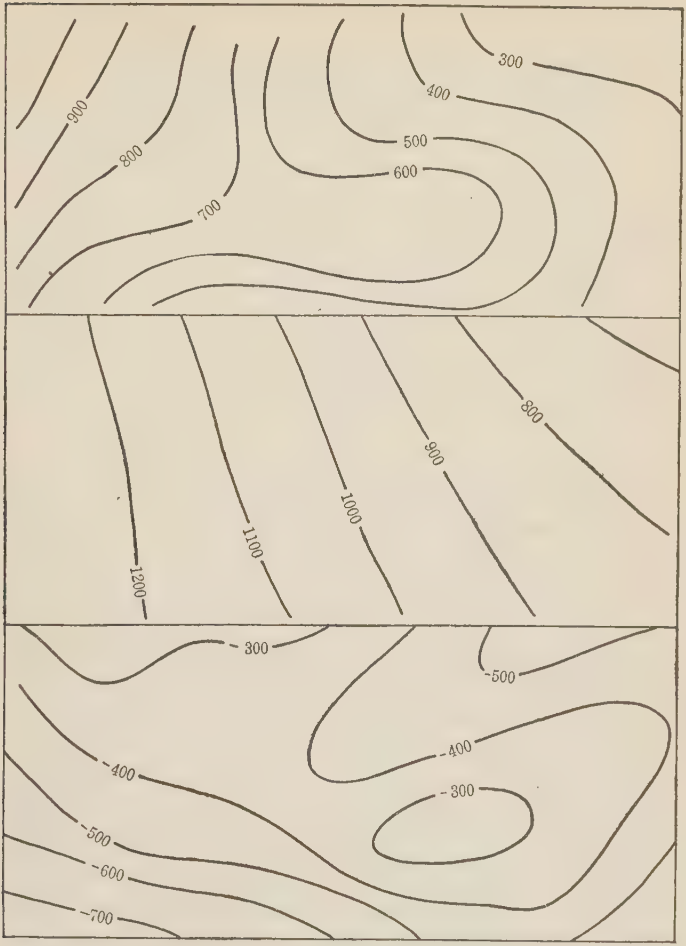

FIG. 147.—Structure contours and convergence map:

Upper: Structure contours on an upper horizon.

Center: Convergence between this and a lower horizon. The lines indicate the interval between the two.

Lower: Structure contours on the lower horizon, obtained by combining the upper with the center figure.

Cross-sections.—The correct interpretation of surface data in the third dimension is the test of a man's ability to see structure in three dimensions. This is usually done by means of cross-sections. A large number of the illustrations in this book are cross-sections, and where more than one is given of the same structure, it is apparent that several interpretations may be put on observed facts. (See figures.)

Cross-sections depict the known and inferred structure as shown on a vertical plane cut through the rocks. They should be chosen at right angles to the strike of the structures it is desired to bring out. They are often drawn in more than one direction across a given area to bring out the varying relations of folds, faults, and igneous structures. The procedure in constructing them is as follows:

A profile is first drawn, on which are plotted all of the observations along the line of the section. Dips of bedding, faults, and other structures which are to be shown, are plotted with the necessary correction due to variation in the strike from a position normal to the line of the section. The geologist then has all of the *facts* on his section. He proceeds to fill it out according to his interpretation of the regional structure. Every available bit of evidence which will lead him to one conclusion as against its alternatives should be brought to bear. In a region of folding the faults are apt to be thrusts; hence, if he has located faults, but has not been able to measure their dips, it is logical to draw them in cross-section hading to the upthrown side. Evidence of drag folds noted in the field, parallelism of the axes, and the plan of the outcrop of plunging folds should be used in drawing the shape of folds. Examples could be multiplied indefinitely, but enough has been said to show that the proper construction of geologic cross-sections is not a mechanical process, but a study worthy of the most careful analysis.

In drawing cross-sections of regions where the deformation has been pronounced it is most essential that the vertical dimension be on the same scale as the horizontal. If this is not the case the structures are so distorted that they cannot be correctly interpreted, even though correctly drawn. In flat-lying sediments, however, vertical exaggeration may be permitted. Wherever it is used, though, its effect must be constantly borne in mind; otherwise the geologist gradually comes to have an erroneous impression of the structures with which he deals, and may for this reason misinterpret the forces which have formed them.

SECTION IV

MAJOR PROBLEMS OF EARTH DYNAMICS

CHAPTER XV

EARTH GENESIS

The Living Earth. Ancient and modern theories of genesis; the Babylonian tradition; Is the earth dead or dying? Newton's contribution of the idea of universal gravitation; its effect upon theorizing. The Nebular theory of Laplace (1796). Its general acceptance during the Nineteenth century and present disproof. The Planetesimal theory of Chamberlin and Moulton (1903); its development according to the method of multiple hypotheses. The Tidal Disruptive theory of Jeffreys, a specialized derivative of the Planetesimal. Discussion of the two genetic theories; bearing of geology on the alternative views; parallel of the Planetesimal and Tidal Disruptive theories.

THE LIVING EARTH

The planet which we call the earth is a child of the sun, and like its parent star it consists of energy and matter. We are distinctly conscious of the fact that the sun radiates energy; we feel it, live by it. We are equally well aware that the earth is composed of matter; we walk on it, dig it, quarry it. But in either case we are less vividly impressed by the presence of matter in the sun or of force in the earth.

Our thinking is dominated by the inherited notion that the earth is dead, or at any rate dying. The legend developed more than 4,000 years ago in Mesopotamia, in the valley where great floods and darkness very naturally represented that chaos which the mind of primitive man conceived to have been the beginning. It has come down to us in the sacred books of the Israelites. Their poet-philosophers ennobled the barbarous Babylonian tradition and gave it the form in which it appears in the Book of Genesis. They wrote of a world created by a power superior to law. The supremacy of natural law was unknown and, even though science has now established that universal fact, our ignorance continues to impose limitations upon our understanding of nature. We limit the life of the world to a period commensurate with our own brief existence and anticipate an end which, according to our standards, is in fact infinitely remote.

The change which has come over our thinking cannot be better illustrated than by reference to the estimates of the probable duration of existence in the form of living creatures, which were current only thirty years ago. It was clear that the end of our living world must come if and when the sun ceased to radiate heat sufficient to maintain life, and physicists calculated the span thus allotted to us as but a few million years.[1] The estimate was based on the assumption that the heat of the sun was due solely to the compression of its mass by contraction in response to its own gravitative attraction. But the advances made by physicists themselves in investigating the organization of matter have since shown that the atomic and sub-atomic forces capable of being converted into heat are enormously in excess of those that may be produced by simple compression, and it follows that Lord Kelvin's estimates of the possible duration of life were arbitrary. There is now no question that the life-giving radiation of the sun will continue during ages to come far beyond human comprehension.

Life on earth is, however, a different thing from life within or of the earth. We think of the globe itself as being " as dead as a stone " and are surprised when it bestirs itself, as in an earthquake. We need to direct our thinking about our earth and its history in accordance with the fact, for it is a fact, that the globe is highly charged with energy. In that sense the earth is not dead or dying. It is alive and very active.

The organization of force and matter in the earth requires a rational explanation. It is to be sought in the origin of the planetary system which revolves around the sun and of which our globe is a small part. It is useful to realize how small. If the entire solar system, including the sun, be taken as 100, then $99\frac{6}{7}$ per cent is in the sun and only $\frac{1}{7}$ of 1 per cent is contained in all the planet satellites, asteroids, comets, and meteors. The four outer planets, Jupiter, Saturn, Uranus, and Neptune, contain 225 times as much material as the four inner planets, Mercury, Venus, the Earth, and Mars. The exact proportion which the Earth represents cannot be calculated because there is a certain unknown mass contained in the minute planetoids or meteors which are too small to be observed as individual bodies but are known to exist because of the light that they diffuse. If we neglect their mass and remember that the earth is the largest of the four smaller planets, we may estimate that it is about $\frac{1}{1000}$ of $\frac{1}{7}$ of 1 per cent of the solar system.

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[1] Kelvin, Lord. On the Age of Earth as an Abode Fitted for Life. *Jour. Vict. Inst.*, London, vol. XXXI, pp. 11–35, 1899.

Chamberlin, T. C., *Science* n.s., vol. IX, pp. 889–901 and vol. X, pp. 11–18, 1899.

It may be supposed without question that the wonderfully ordered system of the sun and its attendant bodies developed from an ancestral sun which comprised all of their substance. It probably also contained much of the energy, but some momentum may have been contributed by another star, as we shall see. The problem is to determine in what manner the ancestral sun threw off that small portion which now revolves in the planetary system.

THE THEORY OF LAPLACE

The earlier explanations of the origin of the solar system were based solely on gravitation. From Newton (1642–1727) on it has been clear that a dominant, if not the dominant force in the universe is gravitation, the mutual attraction which bodies exert on one another and which tends to hold each body to its coherent mass. By the time of Laplace (1749–1827) astronomers had arrived at the concept of universal control by the force of gravity, and Laplace developed the theory of earth genesis which bears his name. It is briefly stated in a note attached to his great work, " La Mecanique Celeste " (1796). It seems probable that he himself did not attach to it the importance it subsequently assumed in the thought of his successors in astronomy, physics, and geology.

Laplace conceived the idea of a contracting sphere of gas, a nebula, within which was contained all the substance of the sun and its attendants. Such a sphere must have had a radius of considerably more than 3,000 million miles, to include the orbit of Neptune and the matter now concentrated in that outer planet. Contracting in response to the attraction toward its center, while also revolving at high speed, the gaseous sphere might part with matter near its outer surface and thus, from time to time, give birth to a planet. Simple in its broad concept, bold in thought, the theory seized upon the imaginations of men, and for nearly a century the Laplacian theory held the field. It controlled all phases of speculation regarding the past history of the earth.

Laplace approached the study of the solar system as a mathematician dealing with the movements of celestial bodies under gravitative control. He did not take account of their constitution and he could not know that a proof of the fallacy of his reasoning would be found in the activities of the very matter of which the planets are composed. Physicists have now shown that molecules and atoms are in motion, even in solid bodies, and that these movements become very vigorous when the latter are heated to the high temperatures at which earthy substances become gaseous. Even the heavier atoms of the metals move rapidly, though they are relatively sluggish as compared with the intensely active atoms of the light gases. The latter are so light and their movements are so accelerated that they readily tend to fly off into space unless firmly held by the gravitative attraction of a large mass. Now the great gaseous sphere which Laplace postulated would have been exceedingly hot and must have rotated at a very high speed in order that the planets should revolve as they do. The temperatures and the speed have been calculated from the actual conditions of the solar system, and it is demonstrated that hydrogen, for instance, could not have remained attached to the gaseous nebula. It must have flown off. But hydrogen is an important constituent of the earth and sun. Its presence proves that their substance has never formed part of a body such as the Laplacian nebula is supposed to have been, and that the origin of the solar system must be sought in some other mode of evolution. There are other objections to the Laplacian hypothesis based chiefly on discrepancies between the observed motions of the planets and the rates of rotation and revolution which they should have according to the theory. They were well summed up by Campbell.[1] To cite but one instance he says:

> If the central mass condensed to the present size of the sun, the sun's equatorial velocity of rotation should now be fully 400 kilometers per second, in accordance with the requirement of the rigid law of constancy of moment of momentum. The sun's actual equatorial velocity is only 2 kilometers per second.

The subject is more fully discussed by Chamberlin, who presents the results of a joint investigation made by Moulton and himself.[2]

For geologists the importance of the conclusion that the earth was not thrown off from a gaseous nebula in the manner conceived by Laplace lies in the inference that it need not necessarily ever have been molten. If it had contracted from a gaseous condition it must have passed through a liquid stage and have cooled down to its present state. The inference that all the interior within a thin crust must still remain hot enough to be liquid has controlled the thinking of geologists for generations. There is now weighty evidence to indicate that the globe behaves like a rigid solid, but geologists are still divided in opinion on the process of changes by which it has reached the present condition. The inherited idea of a molten stage has been presented by Daly[3] and by Barrell[4] among American geologists, and is entertained by an important English school of which Jeffreys and Joly are the exponents. The reasons for recognizing that the earth has grown by the ingathering of solid material, at least since the assembling of a core, have been stated by Chamberlin, the author of the Planetesimal hypothesis.

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[1] Campbell, W. W., The Evolution of the Stars. *Science Monthly*, vol. 87, pp. 209–235; 1–17, 177–201, 238–255; *189*, 1915.

[2] Chamberlin, T. C., and Moulton, F. R., An Attempt to Test the Nebular Hypothesis by the Relations of Masses and Momentum. *Journal of Geology*, vol. VIII, pp. 58–73, 1900.

[3] Daly, Reginald A., "Igneous Rocks and Their Origin." Pp. 155 et sequi, 1914.

[4] Barrell, Joseph, Origin of the Earth (1916) *in* Evolution of the Earth, Lull., *Yale University Press*, 1919.

PLANETARY SYSTEM

In order that we may have in mind the dimensions of the planetary system the following table is inserted:

TABLE [1]

THE SUN AND ITS DEPENDENTS GRADED BY SIZE AND GROUPED BY PHYSICAL PROPERTIES

	Densities	Diameters in Miles	Mean Radius of Orbit in Miles
A. The Sun	1.415	854,000	

B. The giant group of planets. Highly gaseous bodies.
(Densities low; diameters between 30,000 and 90,000 miles.)

	Densities	Diameters in Miles	Mean Radius of Orbit in Miles
Jupiter	1.25	88,392	480,000,000
Saturn	0.63	74,163	881,000,000
Neptune	1.09	34,823	2,770,000,000
Uranus	1.44	30,193	1,772,000,000

C. The medial or terrestrial group of planets. Solid bodies bearing atmospheres.
(Densities high; diameters between 4,000 and 8,000 miles.)

	Densities	Diameters in Miles	Mean Radius of Orbit in Miles
Earth	5.53	7,918	93,000,000
Venus	4.85	7,701	67,000,000
Mars	3.58	4,339	141,000,000

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[1] CHAMBERLIN, T. C., Diastrophism and the Formative Processes. XI. The physical phases of the planetary nuclei during their formative stages. *Journal of Geology*, vol. XXVIII, p. 476, 1920.

D. The diminutive group of planets. Atmosphereless solid bodies.
(Densities high; diameters ranging from 3,600 miles down to the lower limit of estimating power.)

Bodies		Diameters in Miles
Satellite	Jupiter's III	3,558
Satellite	Jupiter's IV	3,345
Planet	Mercury	3,009
Satellite	Saturn's VI	3,000
Satellite	Jupiter's I	2,452
Satellite	The Moon	2,100
Satellite	Jupiter's II	2,095
Satellite	Saturn's VIII	2,000
Satellite	Neptune's VIII	2,000
Satellite	Saturn's V	1,500
Satellite	Saturn's III	1,200
Satellite	Saturn's IV	1,100
Satellite	Uranus' I–IV	500 to 1,000
Satellite	Saturn's II	800
Satellite	Saturn's I	600
Satellite	Saturn's VII	500
Planetoid	Ceres	485
Planetoid	Pallas	304
Planetoid	Vesta	243
Satellite	Saturn's IX	200
Planetoid	Juno	118
Planetoid	Several exceeding	100
Satellite	Jupiter's I	100
Planetoids	Probably 700 or more ranging downward from	100
Satellite	Mars II	....
Satellite	Mars I	10
Satellite	Jupiter's VI and VII	"small"
Satellite	Jupiter's VIII and XI	"very small"

Planetoids. The smallest order of planetoids probably form the lower end of the series, ranging down to 10 or perhaps even 5 miles.

PLANETESIMAL HYPOTHESIS

Chamberlin and Moulton are the names which will be associated with the further development of theories of earth genesis for a long time to come. Chamberlin, the profound naturalistic thinker; Moulton, the cautious mathematician and astronomer. Their method, which originated with Chamberlin, differs from that of the scientist who proposes a preferred hypothesis and proceeds to prove it. It is known as the method of multiple hypotheses and consists of testing every thinkable theory that has a scientific basis. Each old theory was given recognition and tried out against known facts. The latest advances in knowledge were brought to bear. An hypothesis was considered just so far as it agreed. It was modified if modification would improve its chance of being true. It was discarded only when it failed in critical tests. The investigation has been pursued during thirty years of persistent research. It has resulted in proving the inadequacy of theories proposed by Kant, Laplace, Lockyer, and George Darwin, comprising respectively as initial assumptions the existence of a chaotic mass, a gaseous sphere, a swarm of meteorites, or of a solid which suffered fission by rotation (as the moon from the earth). It has also disproved many variations of these and other hypotheses devised by Chamberlin in his search for the theory which should satisfy the most exacting demands of the known facts. The form in which the theory now stands is known as the Planetesimal hypothesis. Regarding it Chamberlin in 1924[1] wrote:

> Several circumstances concur in making this a fitting time to summarize the progress of this inquiry, so far as it relates to the genesis of the earth. At the same time it is proposed to designate the unworkable factors that are to be dropped out of the further inquiry. Thus far an endeavor has been made to restrain the natural tendency toward final conclusions and to keep all genetic postulates on the trial list, in pursuance of the method of multiple working hypotheses. But in an inquiry in which

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[1] Chamberlin, T. C., Study of Fundamental Problems of Geology, Genesis of Planets. Carnegie Institution of Washington, *Yearbook* No. 23, p. 268, 1924.

absolute determination is unobtainable and whose working value lies largely in its bearing on the later stages of the earth's evolution, the time comes when former trial should give place to conclusions, or at least a closing balance of evidence. It is an essential part of the method of multiple working hypotheses that, after due trial, dead and dying hypotheses should be cleared away to disencumber the field in behalf of more promising studies. As two decades have now passed since the planetesimal hypothesis of the origin of the earth and its planetary kin was put into the competitive list, it seems time to close the trial so far as this inquiry is concerned, and clear the field for further work in the line of what seems to have survived the trial.

We may summarize Chamberlin's discussion, but to understand the full force of his argument students should examine his own presentation.[1]

The Planetesimal hypothesis of the genesis of the earth and other planets rests upon the assumption of an ancestral sun, in no way materially different from the actual sun but comprising within its mass the substance of all the planetary matter that now revolves about it. The actual sun is a very hot sphere of gas. The elements that are also found in the earth occur there, but at temperatures so elevated that they cannot enter into chemical combination with one another. The gaseous condition of the whole mass implies great mobility, perfect elasticity, and high tension. The gravitative attraction holds the entire body to its spherical form with a force which at the surface of the sun is twenty-seven times the attraction of gravity at the earth's surface. There are also powerful forces of radiation which act in opposition to gravity. These may be regarded as relatively steady, conservative forces. On the other hand, because of the high temperature the atoms are in violent motion, traversing paths that are very large as compared with their diameters although exceedingly small by human standards. They must meet, produce, and intensify reactions of a very powerful character, which give rise to turbulent circulation and are normally demonstrated by the cyclones that are called sun spots, as well as by the eruptive activity that produces the great outbursts of flame or prominences.

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[1] CHAMBERLIN, T. C., "Origin of the Earth," 1916. "Two Solar Families," 1928. Scientific papers in Carnegie *Yearbooks* and in *Journal of Geology* (a long list).

These evidences of eruptive activity in the sun are of prime importance in their bearing on the Planetesimal theory, for that hypothesis assumes that the planetary matter was ejected from the sun, was propelled or drawn outward and forward, and thus came to revolve in orbits around the parent body.

Imagine then the sun to have been, as at present, a dwarf star in a state of intense eruptive activity. Assume another star, possibly several times as large as the sun or possibly small and dark, to have passed within such a range that it temporarily counteracted the force of gravity of the sun to a notable degree and stimulated the eruptive forces. Bolts of gas would be shot out from the sun. So much of them as was projected to a distance beyond that at which the sun could still pull them back into itself would be drawn forward as if to follow the passing star, but being held by the sun would begin to revolve around it in orbits whose radius would be the distance to which they had been erupted.

The future history of one of these bolts depends in part upon the inherited motions that it had on leaving the sun. There were two conditions of its birth that endowed the mass with intense dynamic energies. The one is the eruptive activity of the sun, which is thought to have been enormously stimulated by the tidal effect. The other condition is the stress of tension and compression due directly to the tidal attraction. That these forces should nicely balance one another, so that the bolt would leave the sun as a bullet leaves a smooth bore gun with a simple motion of flight, is not imaginable. The tidal effect was not superficial. It affected the deep interior of the sun and the length of the bolt shot out must have been a large part of the sun's radius, which had at least the present value of 433,000 miles (708,000 kilometers). Within such a bolt of gas the rotary spirals, the drag along the sides, the collisions of its parts, the changes of temperature and pressure, necessarily gave it the rolling, tumultuous motions of a great volcanic cloud. The outer end represented the lighter gases of the photosphere; the inner end presumably consisted in larger measure of the heavier molecules that are thought to gravitate toward greater depths in the sun in spite of rising and sinking currents. In a general way this distribution of matter persisted in the swarm of planetesimals that was drawn by the passing star into the orbit the future planet was to follow. The outer part of the swarm consisted of lighter molecules, revolving in somewhat larger orbits, while the inner part also contained heavier molecules and revolved in somewhat smaller orbits. The center of gravity of the swarm would under these conditions lie somewhat on the side toward the sun rather than in the middle.

On leaving the sun the gas bolt would undergo certain very pronounced changes.

Relieved of the enveloping pressure by which it had been confined in the sun, and projected into the vacuum of space, the gas would expand vigorously and in so doing would exhaust its kinetic energy. It would be chilled while still a gas.

Furthermore, the radiation of heat from any molecule in the cloud or aggregate of molecules in a knot would be very rapid, owing to the very low temperature of space. The cloud of gas would become a cloud of dust. Each particle would become a planetesimal; that is, a solid body of minute size revolving in an orbit around the sun.

This conclusion has an important bearing on the future gathering of the planetesimals to form the planet, the laws which govern the dynamics of a swarm of solid particles being very different from those that would control the dispersion of a body of gas. The hypothesis framed by Dr. Harold Jeffreys assumes the latter alternative and deduces the formation of a molten planet instead of a solid one, in the case of the earth. We will consider that alternative presently, but will now proceed to trace the growth of the earth by the aggregation of solid planetesimals, as it was visualized by Chamberlin.

When the bolt was ejected from the sun its substance was subjected to three types of forces, the dispersive forces of the gases, the internal activities of its own turbulence, and the gravitation of its mass toward a center of gravity.

The dispersive force or kinetic energy of the gases was lost in consequence of the expansion and chilling of the mass. During the interval of time required to dissipate the kinetic energy the lighter elements were to some extent driven off and lost to the swarm. The proportion of this loss was larger in the cases of the smaller masses, because of their weaker gravitative attraction, and less with the larger masses. Herein lies a reason for the more gaseous condition of the four giant planets as compared with the higher density of the four inner ones.

The internal turbulence of the bolt was rapidly reduced by the inevitable collisions between the large number of particles moving into the orbit they were all to assume and the relatively less number that moved across that orbit or in a direction opposed to it. Molecules or particles meeting with more or less opposition might vaporize, rebound, shatter, or coalesce, according to the force of the collision or side-swipe and their own physical properties. Those on the outer, more dispersed billows of the cloud would tend to escape and be lost; those in the deeper, denser convolutions would be swept into the general movement. Thus the turbulent bolt would become the procession of planetesimals. Even so, however, the procession would not be well ordered. Billions of its members might pursue parallel paths at about the same speed, but other billions would move in orbits slightly inclined to the others or would travel at different speeds. There would therefore be many touches and overtake collisions of moderate vigor, leading gradually to more perfect parallelism of orbits of the fully organized planetesimals.

The first step toward the formation of a globe from the bolt or procession would be the development of a nucleus or core. Gravity would be the compelling force that would draw the planetesimals together. It is often assumed that gravity is always omnipotent and that bodies must fall together, yet we know that the earth does not fall into the sun nor the moon into the earth, because in either case the momentum of the earth or the moon keeps it revolving in its orbit. Chamberlin has pointed out that nuclei or cores are of somewhat rare occurrence in the solar system. There are multitudes of planetoids that have held their independent courses during all the millions of years of existence of the system, and even the comets lack solid nuclei. It is evident that the formation of a core requires special conditions.

The essential condition for the formation of a core during the infancy of the planetesimal swarm is that the mass shall be large enough to overcome the dispersive forces by its gravitative attraction for its own constituents. That attraction was of course not the same for the lighter and denser constituents. A large part of the former might, and in the case of the smaller planets did escape. The denser constituents alone possessed sufficient gravity among themselves to assemble and gather intimately together to form a nucleus. We have found reason to think that they came from deeper layers in the sun and were dominantly present in that bolt nearer the sun. The center of gravity of the bolt and of the planetesimal swarm would, therefore, lie nearer to the sun than the middle between the extreme outer and inner orbits. We should also bear in mind the fact that we are not dealing with mathematically precise conditions. Observation shows that all eruptions from the sun include knots surrounded by more diffuse clouds, and there is every reason to suppose that some similar knot would become the initial nucleus. The knot might by coincidence lie at the mathematical center of gravity and would gravitate toward it, but the relation of the two introduces the element of chance for which mathematics makes no provision.

Once a nucleus was formed its power to add to its mass would depend upon its sphere of control; that is, upon the radius of the sphere within which its attraction for planetesimals was superior to the attraction of other nuclei or of the sun. The motions of the planetesimals themselves constitute a factor in this balance of attractions, and the complexity of relations in such a system as that of the sun and the eight or more swarms from which the planets are thought to have developed escapes our analysis. But the fact that there are eight planets and also many planetoids shows that at least eight centers of aggregation became dominant; and furthermore, that the eight did not succeed in gathering all the planetesimal material.

The heavy planetesimals that gathered in the initial nucleus were small and cold. The impacts of their meetings were slight and presumably not violent enough to cause melting; or if melting occurred the resulting mass was too small long to avoid cooling and solidification. If several knots formed independent nuclei and grew to more notable size before they came together, their impact might melt them in part or entirely, but even so the resulting core would be without atmosphere, a naked little planet in space at the temperature of absolute zero, and could not long remain melted. Thus we are led to the concept that any planet of the size of the earth must have grown up from a solid beginning and has probably been solid throughout its history. This conclusion sharply distinguishes the Planetesimal theory from those variants that have been developed from it. We may next consider the principal one of them, the Tidal Disruptive theory of the origin of the earth, by Jeffreys.

TIDAL DISRUPTIVE THEORY

It is interesting to note that Chamberlin, the geologist, reached the conclusion that the earth must have grown up as a solid rather than that it condensed from a gaseous condition. One might perhaps suspect that he had a preference for terra firma, but it is a fact that he first satisfied himself that the dispersive energy of any gaseous mass which might be ejected from the sun would prevent the material from gathering to form a planet. Astronomers, on the other hand, demonstrate a definite predilection for gaseous bodies. That was true of Laplace and was easily understood before the discovery of the kinetic activity of gases. It is also true, however, of Jeans and Jeffreys,[1] the English astronomers who have recently attacked the problem of earth genesis, that they too assume a gaseous body as the probable state of a planet in its early stages. It is evident that they start from radically different assumptions regarding the sun from those postulated by Chamberlin.

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[1] Jeans, J. H., "Problems of Cosmogony and Stellar Dynamics," 1919.

Jeffreys, Harold, "The Earth, Its Origin, History, and Physical Constitution," 1924.

We have noted that Chamberlin conceived the sun at the time of the birth of the planet to have been a dwarf star very closely resembling its actual condition. Jeans and Jeffreys, on the other hand, start with a primeval sun many times larger than at present, in the gaseous state from which the actual sun may have condensed. According to Jeans, the sun was so distended as to include the orbit of Neptune, some two billion miles (?) Jeffreys regards this as improbable, on the particular ground among others that it would in that case have had an effective temperature of only 200 degrees absolute (73 degrees below zero Centigrade), and therefore, if it could have existed at all, would have consisted of solid dust. The hypothesis that it was initially gaseous would thus break down completely. Assuming a gaseous sun, Jeffreys takes its diameter as something less than that of the orbit of Mercury (36 million miles), and its effective temperature he assumes to have been 3,100 degrees.

Scientists are generally agreed that the tidal effect of a passing star was an essential factor in the birth of the planets, whatever the initial condition of the sun may have been. Chamberlin first proposed this idea, and it is an important, though not necessarily the most important factor in the Planetesimal hypothesis. Jeffreys adopted the idea from Chamberlin, but makes the attraction of the passing star the principal force, if not the only one, to which the ejection of the planets from the sun may be attributed. He reasons that the star was several times more massive than the sun, that it passed the sun at an appreciable speed yet exerted an attraction upon it during some interval of time, and that it drew out bodies of gas which, when detached, collected into nuclei. The nuclei continued to move outwards, but were deflected sideways by the star and thus proceeded to move around the sun in one direction and nearly in one plane. That is to say, these separate bodies of gas obeyed the attractions of the star and the sun exactly in the manner previously deduced and set forth by Chamberlin for the planetesimal swarms.

Jeffreys distinguishes between the condensation of the great planets and that of the minor ones. The former he assumes to have been so massive that they retained all their lighter elements as well as the heavier ones. The smaller planets presumably lost a large fraction of their mass while still in a gaseous state. The remainder cooled at first by the formation of liquid drops on the outside. These, sinking into the interior, accumulated there and formed a liquid core. When all the mass of the planet had assembled it would still be in the liquid stage, but would pass into the solid state by cooling from the surface. The rate of cooling would diminish as the crust thickened and would eventually become so slow that molten bodies might remain included within the earth for an indefinite period.

In a chapter especially devoted to the thermal history of the earth Jeffreys follows Kelvin in postulating the formation upon the molten globe of a solid and relatively dense crust which would break up and sink. The sinking fragments would be remelted and the process would continue until the heat energy became so reduced that they would remain solid. Thus the condition of the primitive earth would be that of a " honeycombed solid, the cells being still filled with liquid. Heat would be gradually conducted out of these, and solidification would thus proceed until complete."

DISCUSSION OF GENETIC THEORIES

In the discussion of theories of genesis of the earth much stress is usually laid upon the relation of initial assumptions to the conditions that may reasonably be postulated as existing or having existed during the evolution of a star or of a planet. These are astronomical conditions. Geologists are as a rule not familiar with them nor with the mathematical forms of analysis by which astronomical physicists reach conclusions. On the other hand astronomers are rarely intimately acquainted with the facts of geology, against which it is appropriate to check the results of their reasoning. The speculation that springs from a gaseous star must come to rest on the solid earth.

Geologists would be better able to guide astronomical assumptions if they were agreed among themselves as to the evolutionary history of the earth since it became a planet and as to its present condition, but our knowledge is not definite and can be differently interpreted by different mentalities. Astronomy and geology are both advancing and changing the point of view. It is wise to cultivate multiple hypotheses and suspend judgment, since to-morrow is likely to bring new evidence.

Even so, we may fairly endeavor to determine the trend of the argument by weighing the two dominant theories, the Planetesimal and the Tidal Disruptive theories, in the balance of our actual understanding of the solar system and the terrestrial globe.

The initial divergence of the two theories is found in the assumptions regarding the condition of the sun at the time of the visit from a passing star. Was the sun then a giant star, a sphere of gas at a relatively low temperature, or was it a dwarf star which though still gaseous had in condensing acquired a much higher temperature and more vigorous internal state? There is nothing by which to fix the date of the momentous visit from a celestial wanderer. His passing near the sun was an accident, which might occur at any time, once in an eternity of billions of years. It had no relation to the condition of the sun then or now. The astronomer is free to follow the logic of his thinking and postulate a sun of relatively cool gas, the ancestor of the actual sun of very hot gas, within which temperature and pressure struggle for mastery and matter passes possibly from the gaseous to the liquid or even to the solid state and back to its previous condition as one or the other force locally predominates.

The cool giant sun would be competent to hold its gaseous mass by its own gravitative attraction. It does not follow that a fraction of it would. The mass of the fraction would determine whether it could or not. Jeffreys calculates that the self-gravitation of a filament, which when drawn out of the sun had succeeded in assuming a spherical form, would hold it together if it had a radius not smaller than about one-sixtieth of that of the sun. The mass indicated is intermediate between those of the great planets and those of the terrestrial group.

This result rests upon assumptions that only astronomers, perhaps, may challenge, but the thoughtful student may nevertheless raise certain questions. Jeffreys names two factors that would make a gaseous filament tend to dissipate, to wit, the tendency of a gas to spread itself out into the surrounding vacuum, and second, the tidal disruptive action of the sun itself. Only the former of these is represented in the mathematical equations. Hence it would appear that the primitive planet was still exposed to disruption by the attraction of its own parent. We may also ask whether the star, which is assumed to have been more massive than the sun, could have passed out of the scene of action without having exerted a tidal stress which might have prevented the filament from assembling as a sphere. We may further inquire what of the turbulence of the primitive sun, without which it is difficult to suppose that the heavier molecules that occur in the planets could have been included with the lighter gases in the filament. Did the filament immediately become a passive body? If so, why? And did it not possess any moment of rotation or if it did was not the centrifugal force a factor to be considered in calculating the necessary self-gravitation of the planet?

Thus upon careful examination it appears that the limited conditions postulated by Jeffreys constitute a special case that lacks some of the factors which would inevitably enter into any natural occurrence. Chamberlin [1] gives a more comprehensive analysis in fundamental studies and he stated his more maturely developed views in The Two Solar Families.

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[1] Chamberlin, T. C., Diastrophism and the Formative Process, XII, The physical phases of the planetary nuclei during their formative stages. *Jour. of Geol.*, vol. XXVIII, pp. 481–504, 1920.

Ibid. "The Two Solar Families," 1928, pp. 14-23, 27–52, and 152–182.

Ibid. The Earth, etc. A review of the work by Harold Jeffreys, *Jour. of Geol.*, vol. XXXII, pp. 606–716, 1924.

Jeffreys, Harold, Reply. *Am. Jour. Sci.*, vol. 9, pp. 395–405, 1925.

in contrast to Jeffreys' inert and passive giant Chamberlin's sun was an exceedingly active dwarf. Chamberlin postulates that the agencies engaged in pushing solar matter away are nearly in equilibrium with the sun's gravitative power, so that only a relatively small propulsive force gives it competency to send solar substance, or selected portions of it, to the limit of the sun's control. It is well to note what the contesting forces are or may be.

The sun holds its substance with the gravitative attraction of its great mass. Within its own body the temperature is so high that all matter is converted into atomic gas. The atoms are in violent agitation, darting to and fro at very high speeds, colliding, rebounding, according to the habit of hot gases. Near the sun's surface they are somewhat cooled and may combine into molecules. Within its atmosphere they are heated and descending molecules are dissociated. Strong convection currents are set up similar to those which give rise to cyclones in our atmosphere, but immeasurably more violent, and they cause the cyclonic funnels whose open ends appear as sun spots. Powerful electric and magnetic fields develop. There is intense radiant pressure, light pressure, directed from within outward, and there are in all probability forms of energy unknown to us because peculiar to conditions of atomic disintegration and reorganization that transcend anything we can observe.

The phenomenon of greatest interest in connection with earth genesis is the occurrence of those eruptions which produce the so-called prominences. A prominence is a gigantic flame, a burst of hot gas that rises high above the edge of the sun's disc and appears as a glowing cloud against the darkness of space. Many of them have been observed, measured, and photographed. Pettit has listed twenty-four eruptive prominences whose rates of ascent and changes of form have been analyzed in the effort to determine their laws of motion and other characteristics.[1]

The striking fact demonstrated by this study is that the eruptive prominences ascend as if independent of the attraction of the sun's gravitation or as if propelled by a superior force which obscures the effect of that attraction. Springing from the sun's surface, the flame rises with great speed and may also move laterally very rapidly. In some cases it bends down and in part reenters the chromosphere, but a large portion is propelled upward and being torn off floats away like a cirrus cloud of extreme lightness. It does not float, however; it is pushed away. After remaining uniform for thousands of miles the rate of ascent is suddenly increased and continues with the accelerated velocity for other thousands of miles. Further impulses are communicated to the luminous cloud and it finally disappears, presumably becoming invisible by cooling. When lost to sight it is still rising with the maximum velocity, which has been observed to attain as much as 200 miles per second.

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[1] Pettit, Edison, The Forms and Motions of the Solar Prominences. Yerkes Observatory Publ., Vol. III, pp. 205–240 with Plates, 1920.

The maximum height observed is obviously not the ultimate height attained. We do not know what the latter may be nor can we set any limit to it. The former frequently amounts to 200,000 or 300,000 miles and a height of 450,000 miles has been recorded. It is the distance to which the flame retains its glowing temperature and therefore may be assumed to vary with the density of the cloud. It is a very tenuous cloud,—a cloud of atoms or molecules.

Pettit attributes the impulses to a periodic force acting for a short interval and with a violence which increases continually. He says:

> Nearly any periodic force capable of repelling gas molecules would satisfy these conditions. Probably the periodic ejection of showers of electrons from a disturbed area in the photosphere would satisfy the conditions. The high velocities of these bodies would cause them to yield their energy to a number of gaseous atoms before they were brought to rest by attaching themselves to one of the atoms higher up in the prominence, thus distributing the repulsive force throughout its mass. The speed (17,000–150,000 km/sec.) would permit an electron to move from bottom to top in a few seconds. . . . There is at present no positive evidence of the existence of the periodic showers of electrons referred to above, and such a hypothesis must be considered as only a tentative possibility (p. 329).

Impressive though the observed outbursts from the sun appear to us, it is desirable to remember that they are very small indeed compared with the eruption necessary to produce a comet and quite insignificant compared to the ejection required to project a planetary mass to its orbital distance. Chamberlin postulates that the comets are indeed direct offshoots of the sun alone and attributes them to extraordinary conditions of eruption, the causes of which reside in the known and presumably also in the unknown activities of its interior, the heat, the molecular and atomic energies, and the even more intimate sources of energy at which we can only guess. In our ignorance we cannot deny that these forces may be competent, not only to drive out the substance of a comet, but possibly also the mass of a planet. The latter seems improbable, however, and doubt is strengthened by the fact that simple eruption cannot well direct the erupted mass into the orbit of a planet. Still less is it probable that the eight larger planets and all the planetoids should have been erupted in the narrow disc in which they now revolve without the aid of attraction by a passing star. Thus the unique characteristics of the planetary family are attributed to the cooperation of the star with the sun, while the erratic behavior of the comets is explained by the inference that they are the children of the sun.

Some astronomers are inclined to think that the observed forces of the sun are incompetent to throw off comets, and to doubt the probability of eruptions sufficiently violent to eject planets, even under the influence of tidal disturbances due to a star. They hold an agnostic attitude, the position of a man who has seen a geyser in action but has not witnessed an eruption of Krakatoa.

BEARING OF GEOLOGY ON THE ALTERNATIVE

The student who finds the atmosphere of astronomic speculation somewhat rarefied may wish to return to earth. We may there test the two theories by their dynamic results in comparison with the actual state of our planet.

The earth is actually highly charged with energy, which appears in various forms, but a conspicuous part of which is heat energy. The heat has been derived from potential energy, which was greatest when the mass was most distended and which ceases to become a source of available energy if the mass reaches a condition of density at which its own gravity can no longer produce effective concentration. Thus the potential energy was greatest, according to Jeffreys' theory, when the mass of the planet was gaseous, or, according to Chamberlin's view, when the planetesimal swarm was most dispersed.

Considering the process of solidification of the planet from the gaseous state, we find the potential energy to have been lost first in the condensation of the gas to liquid droplets, second in the fall of the drops toward the center until a molten globe was assembled, and third in the solidification of the melt by radiation from the surface and subsidence of the crust. The honeycombed solid earth with pockets of magma would retain but little of the original potential energy.

According to the Planetesimal hypothesis of aggregation the nucleus or core may have passed through a process of liquefaction and cooling similar to that just described, or it may never have been liquefied as a whole. Assuming, however, that it was, the mass so solidified was not more than one-eighth of the total mass and the potential energy of the remaining planetesimals was comparatively great as they assembled on the growing earth. The process of gathering in consequence of planetesimals meeting where their nearly parallel orbits crossed or by falling in as the earth grew large enough to attract them to it was very gradual. Chamberlin estimated the average size of a planetesimal at one-fiftieth of a pound and calculated that one planetesimal must have fallen upon each square foot of the core every eight days, if the period of growth has covered three billion years, or one every five days if the growth has been accomplished in one billion eight hundred million years. The rate of compression implied by these estimates is exceedingly slight. It means nothing at the surface, but would become effective as a source of heat a few miles below the surface, where the heat energy would be blanketed and retained by the mantle of relatively non-conducting rock. Loosely aggregated at first, but slowly buried and compressed, the envelope assembled around the core would charge the globe with a large amount of heat.[1]

Our question is which of the two conditions is more nearly in accord with the evidences of activity since the earth solidified to the extent that it possessed a permanent and solid crust that records its dynamic history? Do the ancient rocks bear witness to moderate deforming forces and does the record of growing continents and mountain chains indicate that those moderate activities have died down? Or is there evidence that the earth has been and still is very vigorous? The latter is unquestionably the fact. In the chapters that follow the evidence of the hot interior, of intense eruptive activity, and of energetic mountain growth is outlined. The facts leave no room to doubt that man, the latest comer, lives on a living, not on a dying earth.

It appears to be true that the Tidal Disruptive theory of the origin of the earth, as formulated by Jeffreys, represents a special case and fails to take account of essential dynamic conditions, that would materially modify the assumptions on which the mathematical treatment rests. The conclusions are therefore not reliable. They do not accord with geologic evidence.

The Planetesimal theory was framed after all forms of gaseous theories had been tested and found wanting. It is not a preferred hypothesis, but a surviving one. Its conclusions are in accord with geologic evidence as we understand it.

Appended is a parallel statement of an analysis of the two theories, which may help toward the formation of an independent judgment as to their merits.

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[1] CHAMBERLIN, T. C., Diastrophism and the Formative Processes. XIII. The Bearings of the Size and Rate of Infall of Planetesimals on the Molten or Solid State of the Earth. *Jour. of Geol.*, vol. XXVIII, pp. 665–701, 1920.

Ibid. Op. cit. XV, *Jour. of Geol.*, vol. XXIX, pp. 679–700, 1921.

ORIGIN OF THE EARTH

PARALLEL STUDY OF TWO THEORIES

The Planetesimal (Chamberlin and Moulton)	*The Tidal Disruptive* (Jeffreys' modification of Jeans' theory)
INITIAL POSTULATES	
For many years these two students had examined the distribution of masses and the dynamical endowments of the planetary system, and they used these data as the basis on which to frame a rational theory of the earth's origin. Using the method of multiple hypotheses, they had tested and disproved all theories of gaseous or meteoritic origin. The Planetesimal theory was the logical result of further search for alternative modes of origin.	Tidal disruption of the sun, previously postulated by Chamberlin as an essential element of the Planetesimal theory, is adopted and elevated to the position of a first and only cause of the birth of the planets.
The sun at the time of the birth of the planets is assumed to have been a gaseous star, very similar to the actual sun, a dwarf star.	The primitive sun is assumed to have been a gaseous star in the giant stage, strongly condensed toward the center, not more than 21 million kilometers in radius.
The sun is assumed to have been endowed with great internal eruptive and propulsatory energy then as now.	Sun's activity not regarded as an important factor.
A passing star stimulated the eruptivity of the sun and caused four double eruptions from the eruptive belts.	A passing star created disruptive tidal effects through its gravitative attraction only.
Assumptions regarding the star are not rigorously limited, Moulton having by a mathematical study of 48 cases shown that any one of a number of working subhypotheses might give rise to matter circulating about the sun at planetary distances.	The star is assumed to have been much more massive than the sun. The possibility of reciprocal tidal action of the sun on the star is disregarded.
The star passed at a high speed in an open hyperbolic orbit.	The encounter of the sun and the star is described as neither slow nor transitory but of an intermediate type.

Postulates Regarding the Planetary Substance

The material substance of the planetary system was originally a part of the gaseous sun.	The material substance of the planetary system was originally a part of the gaseous sun.
This substance was endowed by the passing star with a large proportion of the total great momentum now possessed by the planets, in contrast to the relatively small momentum of the massive sun.	The contrasts of masses of the sun and planets and of their momenta are not discussed and apparently not considered.
While still in the sun the substance that was to become a planet shared in the turbulent state of the sun and received additional energy in the process of expulsion by the tidal effects.	The internal energy of the gas in the sun is not mentioned and the discussion of conditions after disruption does not take account of it.
"Earth bolt shot from the sun."	"Filament drawn out or shot out from the sun."
The planetary bolt is assumed to have been endowed with cyclonic rotational motion and other activities, like a rolling cloud.	The ejection of the filament is discussed as having been encouraged by "fluid pressure."
Emphasis is laid on the dispersive effects produced by the kinetic energy of the gas, the cyclonic and evortical activities of the bolt, and the release of pressure in passing from the body of the sun into the almost absolute vacuum of space.	Dispersive activities of the filament are assigned a minor role. It is assumed to retain its form under its own gravitational attraction.
The form assumed by the substance of any planetary bolt is that of a swarm drawn into a broad orbit around the sun. The original cyclonic and evortical motions persist in the swarm though modified by the change in environment. There is a strong tendency to dispersion at the outer end of the bolt where lighter molecules prevail, and less tendency at the rear end where heavier molecules predominate.	The form of the whole filament is described as that of a long protuberance toward the star which, in case of steady joint influence of the sun and star, would resemble a " boomerang," somewhat thicker in the middle than at the ends; it would condense toward any center of slight distortion causing a local increase of mass per unit of length.

After Leaving the Sun

The rapid expansion of the mass and the radiation of energy into space soon induced cooling and solidification, forming solid atoms, molecules, or accretions. All of these may be planetesimals if they behave dynamically like planets. The essential thing is that the swarm took on an orbital organization in contrast to the gaseous organization. In that dynamical change lay its chance to assemble and form a planet.

The formation of a liquid or solid core was the beginning of aggregation of the swarm of planetesimals. It could have occurred only among planetesimals having concurrent orbits that were not strictly parallel and in which speeds were not the same. If revolving in these relations planetesimals would come together by overtake collisions and side-swipes. In these mild encounters the more elastic might rebound and suffer a partition of energy; the more brittle might break; but the heavier silicates and tough metallic constituents would coalesce. When erupted from the sun the material of the swarm was already less dense at the outer end of the bolt and denser at the inner end. Thus density conditions favored the assemblage of a core near the inner end where the inrolling motion was also favorable.

The growth of any core depended upon the amount and density of the material moving in concurrent orbits and later upon its sphere of control. The latter was determined by competition with other planetary cores and with the sun.

When the length of the filament reached a value calculated as a function of the velocity of sound in the gas, the density, and the gravitational constant, it detached itself and began its existence as a separate body, unless it fell back into the sun. It separated into segments which, if they continued their separate existence, became independent planets.

The length and thickness of a segment of the filament at rupture would be comparable, and it would assume a nearly spherical form without alteration of the order of a magnitude of its density. It would thus form a gaseous sphere.

Since gas tends to spread into a surrounding vacuum the gaseous planet must have had at least a minimum mass in order that its gravitative attraction might hold its substance and prevent dispersion. The minimum radius of any primitive planet is calculated to have been about one-sixtieth of that of the primitive sun.

The gaseous body of a great planet condensed by radiation, liquid drops forming on the outside and falling inward under gravity. They would collect with the densest at the center and liquefaction would set in and proceed until complete. The smaller planets, from twice the mass of the earth down, would behave in part as the larger ones do, but because of insufficient gravity would probably lose a large part of their mass.

The core thus gradually drew to itself the available planetesimals within its control and became the planet without having necessarily passed through a liquid state at any stage.

All planets must pass through a completely liquid state. Solidification would result from the formation of a crust, which would break up and sink in the molten globe, gathering at the center. The solid mass would increase in proportion to the magma until the whole became a honeycombed solid with liquid pockets.

The parallel between the Planetesimal and Tidal theories brings out the fact that they have in common only the assumption of a tidal effect produced by a passing star. This concept was first worked out by Chamberlin and Moulton and was adopted by Jeffreys, who built on it an entirely different hypothetical development.

The initial difference lies in the assumption regarding the condition of the sun at the date of birth of the planets. Chamberlin based his deduction on the actual conditions. He assumed that the sun was then as now, a vigorously eruptive dwarf star, and attributed the expulsion of the planetary substance to that eruptivity, plus the stimulating tidal attraction of the passing star.

Jeffreys says:

> It seems unlikely on several grounds that a dwarf star could have been as heterogeneous as the present (Tidal) theory requires. Thus the origin of the planet must have happened while the sun was in the giant stage. It was then a gaseous star.

It is difficult to follow this statement, since the actual sun, a dwarf star, is known to be sufficiently heterogeneous to contain the principal elements found in the planets. The important conclusion that the sun *must* have been in the giant stage is thus left without supporting reason. We might admit that it may have been, but the coincidence of the passage of the star with the particular instant when the sun had a certain radius, density, and temperature, required by an arbitrarily selected theory, would be quite fortuitous. The habit of thought of the mathematician is illustrated by Jeffrey's postulate that the time "*since the solidi-*

fication of the earth is 1.6×10^9 *years or* 5×10^{16} *seconds*" (page 85). What does it mean to convert the incomprehensible era of one and six-tenths billion years into 5 quadrillion seconds? What is the concept of solidification that permits its conclusion to be dated to a second?

This is a characteristic example of the difference in methods pursued by the two investigators. Chamberlin reasons from the known facts; Jeffreys seeks a condition that fits his hypothesis. This is an intellectual difference, and neither type of mind is likely to be able to follow the arguments of the other with confidence.

Either the Planetesimal or the Tidal theory of the origin of the earth would serve as a basis for deductions regarding continental genesis, but careful study indicates that Jeffreys' brilliant mathematical abstractions relate to ideal conditions whereas Chamberlin's reasoning keeps constantly in touch with reality. To a geologist accustomed to keep his feet on the ground, the latter seems the surer guide to the truth.

A grave objection to the Tidal Disruptive theory of Jeffreys, as to any other theory that requires solidification of a molten globe, is the very limited endowment of energy left to the earth in its primitive stage. The potential energy of infall of its substance, together with the latent and sensible heat of the magma, is all expended. The honeycombed solid [1] would be very inadequately supplied to continue its activity throughout a billion years or so, as the earth has done. The planetesimal earth, on the other hand, would retain the potential energy ot infall as internal heat, and would be so conditioned that it could continue active down to the very present, as is the case with our globe.

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[1] As this manuscript goes to press a letter is received from Professor Jeffreys stating that he no longer entertains the concept of cooling that would produce a honeycombed earth, since L. H. Adams has shown that the earth would solidify steadily from the bottom upwards. He proposes to adopt Adams' view in the second edition of the Earth. It may be observed that this conclusion leaves the globe with a still lower endowment of energy, since solidification would be complete and radiation of energy from the molten surface would exhaust the resources of potential energy of gravitation and the latent heat given off in solidifying.

CHAPTER XVI

CONSTITUTION OF THE EARTH

Knowledge and surmise. Kinds of material: the outer skin; the lithosphere; the inner globe. Distribution of densities; relation of surface density to that of the whole globe; change in depth; evidence of seismology—inferences from the paths of earthquake waves and their speed; evidence of petrology—deductions from investigations of igneous rocks. Discussion of the evidence; its limitations; the alternatives of a once molten earth or one formed of solid planetesimals.

LIMITS OF OBSERVATION

From here to the center of the earth is about 4,000 miles (6,400 kilometers). By means of mines and borings we have penetrated to the depth of about one and one-half miles ($2\frac{1}{2}$ kilometers) from the surface toward the center, and we thus know by observation the constitution, mechanical condition, and temperature changes to that skin-depth. Definite observation of the rocks formed immediately under the outer surface is made possible where they are exposed at the surface in consequence of gradual uplift and erosion. There are large areas in the continents, the so-called continental nuclei (see Dana), where rocks are mostly such as have crystallized from a melted condition and have recrystallized while being squeezed out; that is to say, sheared. These are the Archean rocks and younger bodies that have been similarly affected. They took on their present character when buried some miles below their present situation, probably 10 to 20 miles (15 to 30 kilometers) below the surface. We infer, therefore, that the appropriate conditions of variable temperatures and variable pressures exist at those depths, for the heat must at times have been high enough to melt the rocks and at other times only so high as to cause them to recrystallize without melting; while the pressures must have been unequal and variable in order to squeeze, shear, and draw them out.

Direct observation of what lies below the depth of perhaps 10 miles (14 kilometers) below the surface is not possible. We are thrown back upon lines of inference of more or less uncertain character.

To what depth is the globe composed of the crystalline rocks we observe at the surface? They are silicates of a few metallic bases: alumina, iron, lime, magnesia, soda, and potash preponderating. They constitute a shell at least as thick as the depth from which the Archean rocks are raised. The shell of silicates is, no doubt, very much thicker. As soon, however, as we begin to speculate on the question " how much thicker?" we encounter another problem: " what lies beneath?", and the inquiry broadens to include the constitution of the globe as a whole.

EVIDENCE DERIVED FROM DENSITY

We approach this general question of the constitution of the globe directly by considering how heavy it is.

The mean density of the earth as a whole has been determined to be about 5.55 times that of water. The mean density of the lithosphere, assuming it to be no more than 10 miles deep, is about 2.77 (Washington, 1920). Since the lithosphere is so much lighter than the average for the whole earth it follows that the substances in the interior must be of higher density.

There are two conditions which may and probably do affect the density of substances within the earth. The first is compression. The weight which rests upon rocks within the earth and which increases directly with the depth below the surface undoubtedly compresses them and makes them denser than they are at the surface. It has been supposed that this effect might be sufficient to account for the greater density of the interior, but recent studies upon the compressibility of rocks (Adams, Williamson, and Johnston,[1] 1919; and Williamson and Adams, 1923) have shown that compression alone is inadequate and that we must recognize the presence of materials of higher specific gravity than the silicate rocks.

This, then, is the fundamental assumption: the earth consists of a shell of silicates, the lithosphere, and of other, heavier materials which constitute the interior.

Comparing the earth with meteorites, it is inferred that it may consist largely of the substances found in them. They are in part stoney, but in larger part they consist of metallic iron with some nickel. This fact suggests that a mass of heavy nickel-iron lies within the earth, and that it is large enough to raise the average density to 5.5 (Washington, 1925). This suggestion is supported by the fact that the earth is a magnet and metallic iron is magnetic, whereas the silicates are not.

The inference that there is a metallic core is very generally accepted. Differences of opinion exist, however, as to its mass and the arrangement of heavier and lighter materials. The geologist reasons from observation that the outer earth is heterogeneous. It is certainly composed of a variety of rocks, so far as we can see them, and the diversity extends at least to the depth of the shell within which the forms of continents, basins, and minor surface features are determined; for they are not arranged according to any well-ordered, symmetrical plan. The limiting depth to which this line of inference can safely be pushed is, however, not great—possibly a hundred miles—and the geologic evidence gives no clue as to what lies immediately below or how the heterogeneous silicates of the lithosphere grade into the next lower shell. The gradation may be very gradual or quite sharply defined, so far as geologic evidence goes.

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[1] Adams, L. H., Williamson, E. D., and Johnston, John, The Determination of Compressibility of Solids at High Pressures. *Am. Chem. Soc.*, vol. 41, 1919.

Adams, L. H. and Williamson, E. D., The Compressibility of Minerals and Rocks at High Pressures. *Jour. Franklin Institute*, vol. 195, pp. 475–529, 1923.

EVIDENCE DERIVED FROM SEISMOLOGY

The student of earthquakes, the seismologist, takes up the argument, bringing to bear the methods of mathematical analysis of elastic earthquake waves which pass through the earth. The origin of a wave, the point at which it is recorded by the receiving instrument, the distance traveled, and the velocity of transmission are the conditions that enter into the calculation. The velocity is the critical factor. For a certain kind of elastic wave, the transverse type, the velocity increases with the rigidity of the material and decreases as the density increases. The waves are refracted like light waves when they pass from one medium to another. By studies of earthquake records it has been found possible to determine the curved or broken paths taken through segments of the earth and the speed of transmission in different parts of the path. It is found that from a depth of 38 miles (60 kilometers) down to 750 miles (1,200 kilometers) the speed increases almost in proportion to the depth—an effect which could only result from an even more rapid increase in the elastic nature of solids. From 750 to 1,060 miles (1,200 to 1,700 kilometers) the increase of velocity is more gradual. From 1,060 to 1,500 miles (1,700 to 2,400 kilometers) it is more gradual still. From 1,500 to 1,800 miles (2,400 to 2,900 kilometers) the velocity decreases slightly. In these last three stages of the path it seems probable that there is an increase of density sufficient to offset the increase of velocity which would otherwise result from higher elasticity. At 1,800 miles there is a marked change. The transverse waves we have been tracing do not penetrate the sphere within that radius. Elastic transverse waves are not transmitted by liquids or gases, and it has been suggested that the interior of the earth within the radial distance of 1,800 miles might be a very dense liquid or gas under conditions unknown at the surface. An alternative is also possible. The core may be so dense that the energy of the transverse wave is not able to penetrate it.

There is another kind of earthquake wave, known as the longitudinal wave. It is a vibration in the direction of the path instead of across it, and it follows somewhat different laws from those that govern the transverse vibrations. Nevertheless, the longitudinal waves show similar changes of velocity from the depth of 38 miles down to 1,800, and also indicate a very marked change of conditions at that depth. But they are not entirely lost. They are strongly refracted and come through the outer margin of the core with greatly reduced speed.

From researches based upon these data Macelwane concludes[1] (1925):

> We find ourselves living on a planet with a surface layer of rock, in places at least, 60 kilometers deep, lying on a mantle of much more elastic material, probably rock, about 1,100 kilometers thick: a transition layer about 1,700 kilometers in thickness made up of three concentric shells, beneath which is a quite different core, probably of heavy metals, such as iron, of three thousand four hundred and seventy kilometers radius.

EVIDENCE DERIVED FROM PETROLOGY

The results of earthquake studies assist the petrologist, the chemical-physical investigator who classifies rocks, to make his contribution to our knowledge of the earth's interior. The petrologist starts with the known rocks and distinguishes primarily two major groups, the granitic and basaltic. The rocks of the granitic group contain a high percentage of silica and are of light weight. The rocks of the basaltic group are relatively high in iron and magnesia and are heavier. The two groups grade into each other through rocks of intermediate composition. Even higher in iron and magnesia and heavier than basalt are rocks of the peridotite group, representing the most basic silicates. Heavier still are the metallic constituents of the earth, among which iron is probably so much the most abundant that the proportion of other metals is negligible in considering the constitution of the earth as a whole.

It might be possible to imagine many different globes composed of these substances in different proportions, any one of which would have the average density of the earth; but speculation is

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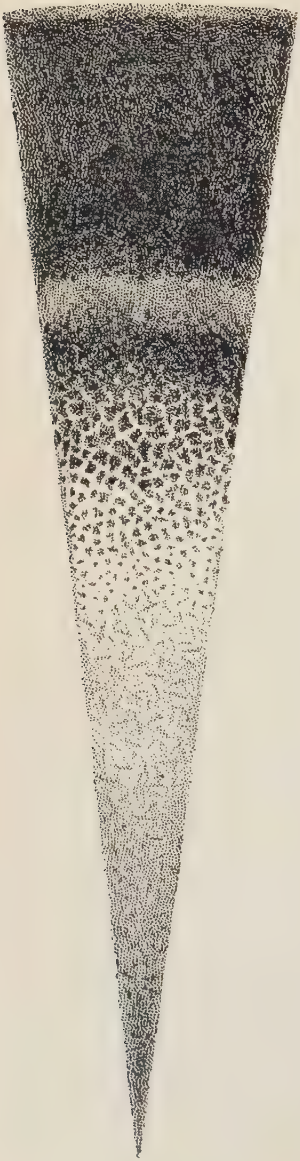
[1] Macelwane, J. B., S. J., The Interior of the Earth. *Bull.* Seismological Society of America., vol. 14, pp. 81–87, 1924.



limited to some arrangement which will place in their proper positions rocks having the density, elasticity, and rigidity required by the velocities of earthquake waves at different depths. Adams[1] (1923) investigated the elastic properties of rocks under high pressures and reached the conclusion that those of the peridotite group are the only ones which will give the higher velocities, unless in the depths of the earth there may be some mineral unknown to us.

Assuming that the earth is composed largely of materials similar to those found in meteorites, Washington[2] (1925) calculated the proportions of several stoney shells and a metallic core, which he arranged in an ideal globe in such a manner as to satisfy the requirements of earthquake observations and to meet the estimates of the geo-physicists. He recognized an outer shell of granitic rocks, 38 miles thick (60 kilometers); an underlying shell of basaltic rocks, 25 miles (40 kilometers) thick; a shell of peri-

Fig. 148.—Constitution of the Earth according to Washington.

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[1] Adams, L. H. and Williamson, E. D., The Compressibility of Minerals and Rocks at High Pressures, *Jour.* Franklin Inst., vol. 195, pp. 474–529, 1923.

[2] Washington, Henry S., The Chemical Composition of the Earth, *Am. Jour. of Science,* vol. IX, May, 1925.

dotite rocks, 960 miles (1,540 kilometers) thick; next a shell in which peridotite is the prevailing, continuous material, but there is a scattered proportion of iron which increases downward; this he names the *ferrosporic* shell and assigns it a thickness of 435 miles (700 kilometers); beneath the ferrosporic he places a *lithosporic* shell of similar thickness, which is characterized by the presence of scattered masses of peridotite in a continuous body of iron; and finally he reaches the core of the earth, a sphere of iron 2,125 miles (3,400 kilometers) in radius. These concepts are illustrated graphically in Fig. 148.

DISCUSSION OF EVIDENCE

In the work of Macelwane, L. H. Adams, Williamson, and Washington we have the latest contributions to the investigation of the interior of the earth. They are the result of exhaustive mathematical, physical, and chemical research, and in Washington's work particularly the results are set forth with a degree of detail which conveys the impression of conclusive authority. The writers themselves disclaim any such certainty, and it is wise to accept their doubts at their full value. The basis of their reasoning, it is true, is in observation and experiment and is the best we have as yet. But they are obliged to proceed upon assumptions that determine in advance the nature of the conclusion. Thus, the seismologist assumes that the earth's core is a smooth sphere, at the surface of which the elastic wave is refracted in a certain plane. If the surface of the core is irregular, the path of the wave would diverge from that which the assumption determines and would be longer or perhaps shorter. A check on this alternative is the multiplication of observations and a concordance of independent results, independently determined.

The physicist can experiment upon the properties of rocks either under great pressure or at a high temperature, but he is not able to handle both extremes in one and the same experiment. But excessively great pressures and exceedingly high temperatures exist in combination within the earth, and the properties of rocks are probably modified by that environment. The estimates of elasticity and rigidity may be affected by this condition.

The chemist deals with the combinations of silicates of the outer shell and their crystalline forms under known conditions. He also is unable to determine what other combinations or what crystalline or colloidal states may exist under the extraordinary conditions within the earth.

It is therefore appropriate to traverse the conclusions as to the interior of the earth with reasonable doubt and to consider what alternatives might be formulated.

The basic fact, regarding which no doubt is admissible, is the existence of material of high density, such as iron, in the core of the earth. It is certainly not only very dense but also very rigid, since Schweydar's[1] work on the tides (1912) demonstrates that the earth as a whole is about twice as rigid as steel; and it would seem to follow that the core must be solid. But the fact that the transverse elastic waves from an earthquake have not yet been recognized as passing through it may indicate that it is dynamically organized as a liquid or possibly a gas of extraordinary density and rigidity, which thus contradicts our usual concepts. It is best described as a *non-solid* core.

The radius of the core is roughly indicated by the seismologic data, but Macelwane's figure of 2,170 miles (3,470 kilometers) is subject to a possibility of error of 30 or 40 kilometers (Macelwane, personal communication, 1928) and differs from Washington's estimate by about 45 miles (70 kilometers). The seismometric determination indicates a sharp boundary between the core and the overlying shell, such as might exist between a sphere of compressed liquid and its envelope, but such as would not be likely to have formed in a mass which had solidified by cooling.

Washington's arrangement does not recognize the sharp boundary indicated by the transverse elastic waves. On the contrary, he postulates the wide zone of transition of the lithosporic and ferrosporic shells, 825 miles (1,400 kilometers) thick. The origin of this idea is evident. It lies in the assumed analogy between the metallic core of iron and a mass of metal which has been melted. The metal would be covered by slag in which the metallic and stoney constituents would be mingled, the former predominating in the lower layers and the latter in the upper layers. Assuming that the earth was once molten and that it cooled down and solidified under quiet conditions which permitted the heavier materials to

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[1] Schweydar, Untersuchungen über die Gezeiten der festen Erde und die hypotetische Magmaschicht. Veröffentlichung der K. K. Preuss. geodät. Institutes. Neue Folge No. 54, 1912.

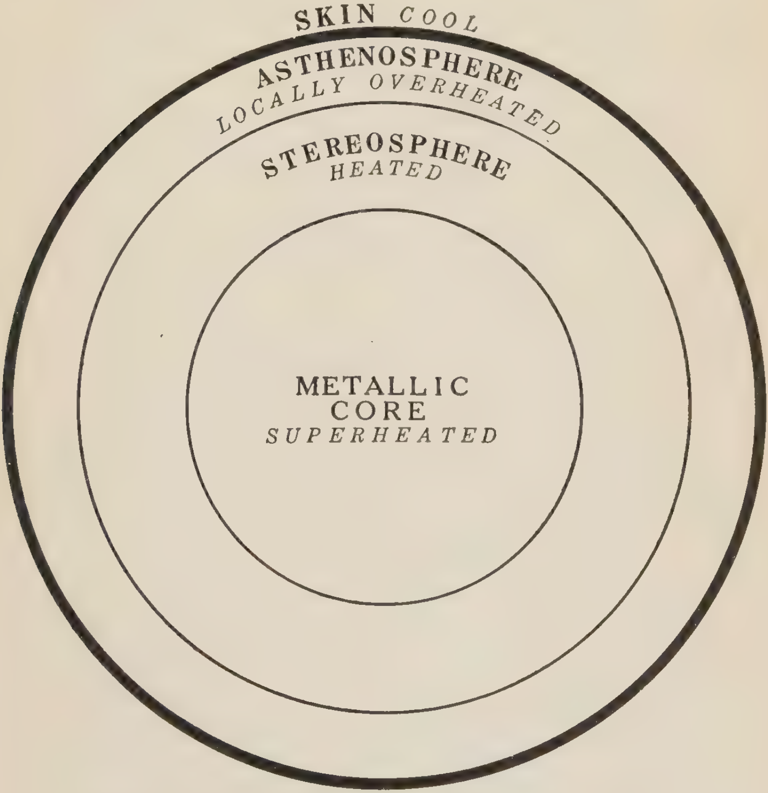

Fig. 149.—Hypothetical dynamic spheres of the Earth.

sink while the lighter floated, an arrangement of silicates and metallic constituents might assume the succession of shells so ingeniously calculated to meet the controlling data. Even so the separation would be incomplete. The melts would be viscous and viscosity would check the sinking of the heavier materials. Boiling and convection would carry them up. In a molten earth only a heterogeneous mixture, roughly stratified by gravity, could result.

The Planetesimal theory offers a different process of development and a different arrangement of materials as more probable. Given the metallic core as a result of the gathering of heavy molecules at the center of gravity of the original bolt, the subsequent growth of the planet was by the gradual infall of planetesimals so constituted that they formed basic igneous rocks. At an early stage of growth the globe became large enough to hold an atmosphere, and from that time on to the present it has been diversified on the surface by the distinction of lands and seas. Land areas, whether large or small, are areas where rocks weather and decompose. The basic constituents; lime, magnesia, iron, etc., are carried away in solution, while the silica is concentrated in continental or near-shore sediments. This method of concentration of silica is at present and presumably long has been only the last step in the process of separation of the acid constituent of rocks, for continents now consist prevailingly of granites and granites are acid rocks produced by differentiation of more basic types. The processes of differentiation originate in the laws of physical chemistry and must have gone on in the earliest magmas. Granite, therefore, separated from more basic types during the earliest development of molten bodies, and land masses of granite were early features of the earth's surface. From them were produced strata of siliceous sands. As the globe grew the sands became deeply buried. Wherever and whenever they were exposed to melting temperatures they combined to form magmas that were more acid than those around them. Thus, a heterogeneous envelope would assemble around the core. That envelope is now 2,000 miles (3,200 kilometers) thick. If, as seems probable, the distinction of lands and seas was a feature of the early stages of growth, the cycle of differentiation, weathering, and remelting must repeatedly have resulted in smaller or larger masses of relatively siliceous rocks enclosed in the general envelope of basic rocks.

It may have happened that the distribution of lands at successive epochs was not similar and that the corresponding, more or less acid bodies developed without relation to one another. But there are peculiarities in the actual arrangement of continents, such as their preponderance in the so-called " Land hemisphere " and their triangular, southward-pointing forms, that suggest a cause back of their existing plan. The Planetesimal theory finds a reason for the distinction of the Land and Water hemispheres in the original arrangement of matter in the bolt from the sun, and attributes the outlines of the continents (in so far as they are systematic) to stresses that affected the growing earth. To the extent that these conditions controlled the positions of the early lands and the subsequent processes of burial, melting, and eruption of masses there was a tendency toward the perpetuation of the continental plan. The actual continents would in that case represent the ancestral continents and give a suggestion of the distribution of more acid, lighter rocks in the deeper parts of the envelope.

Alternative suggestions regarding the arrangement of matter in the interior of the earth are further discussed in the following chapters in connection with the distribution of forces.

CHAPTER XVII

FORCES OF THE EARTH

Geologic changes and the forces involved. Forms of energy available in the earth: inertia, gravitational attraction; atomic and molecular energies; cohesive force; heat energy. Pressure versus heat; confining pressure; differential pressure; mutual relations of heat and pressure. States of matter: solid and (or) liquid. Summary regarding forces.

GEOLOGIC CHANGES AND FORCE

Change has characterized geologic history throughout all time. The areas of lands and seas; the configuration of lands and sea bottoms, represented by plains, plateaus, and mountains, or by deeps and shallows; the activities of volcanos and their distribution; all those features which constitute "terra firma" have actually always been changing and are now changing in form or elevation. The impression of permanence that we receive comes from the fact that we cannot follow the slow processes long enough, as a rule, to observe the changes. Universal change is recorded, nevertheless, as having characterized the earth's surface during all geologic ages.

To illustrate: The Colorado river has cut and is cutting the Grand Canyon, but the effect cannot be observed in a lifetime; no, not in a thousand years. The Colorado plateau has been and is being raised, but the change in altitude will not become apparent in ten thousand years.

Infinitely slow are the processes of change in the globe. If, perchance, there occurs some violent action—a volcanic eruption for instance—it represents the sudden yielding of stubborn resistances to forces that have long been gathering. The action is very local and is but a momentary incident in some more general and prolonged effort of force.

Force is essential to change. That is evident. It is not equally evident that force is essential to that condition which we call stability. But that is the fact. Consider a mineral, quartz for instance. It is a chemical compound in which silicon and oxygen are united by bonds of force. Each molecule is a balanced system of attractions and repulsions. The molecules arrange themselves in a permanent crystalline form that is in turn determined by the balance among their mutual adjustments. The chemical compound is stable because the balanced forces are powerful. The crystal of quartz is enduring because the inter-molecular bonds are strong.

Thus, force is essential to stability as it is to change, with this difference, however: stability is an effect of balanced forces; instability and change are caused by unbalancing forces.

We may take quartz again as an illustration. If that very permanent mineral be heated to 1,472 degrees (800° C.); that is, if energy be supplied to agitate the molecules but not sufficient to cause melting, then the crystalline structure changes and the chemical compound of silica and oxygen becomes the mineral that is called tridymite. The molecules have assumed a more open order, as is shown by the change in specific gravity (quartz 2.654, tridymite 2.318) and the change in their arrangement appears in the new form of the crystals. The previous balance has been disturbed by the heat energy added to the system, and a new balance has been established.

It is desirable to form some concept of the amount of energy involved in a terrestrial change. It has been estimated, for instance, that a single earthquake shock released enough power to run the largest British battleship 38,000 years (Mendenhall). Another, even more powerful, presumably released energy sufficient to throw a ton to a distance of 12,000 million miles (Reid, 1910). The force in these instances was in the nature of an elastic rebound, a snap of a spring, as it were, and the release took but a few seconds. But the accumulation of elastic energy had taken many decades.

An earthquake is an instantaneous and negligible incident in the growth of a mountain range. Let us endeavor to suggest the order of magnitude of the forces that are involved in the development of such a range as the Sierra Nevada of California.

The Sierra Nevada consists chiefly of granite—rock that was once molten, was squeezed up from the deeper, outer part of the earth, intruded into the upper, superficial part, and solidified by cooling. The granite may have been some fraction of a much larger body of more basic magma formed by melting, but for the present purpose we will assume that there was a mass, equivalent in volume to the Sierra Nevada, lying at a depth of 50 miles (80 kilometers) below the surface; that it had the temperature of that level, which we will take to be 1,000 degrees F. (say 500° C.) below its melting point; and that the rock was therefore solid. We assume that it had to be melted.

The exposed granite mass in the Sierra Nevada is 400 miles (640 kilometers) long, 75 miles (120 kilometers) in width, and 5 miles (8 kilometers) thick. It extends under the surface an unknown amount and is no doubt larger. Let its cubic volume be taken at 200,000 cubic miles (800,000 cubic kilometers). This figure involves no unreasonable volume, since much larger masses of granite than that of the Sierra Nevada are known.

We may first calculate the amount of heat energy required to raise the temperature of this mass 1,000 degrees F. to the melting point. Assuming that no heat is lost in the process, the granite will then by assumption be at the melting point, but not yet melted.

The factors required are the weight of a cubic foot of water, 62.5 pounds; the specific gravity of granite, 2.7; the specific heat of granite, say 0.2; and the volume of granite in cubic feet.

We take the weight of a cubic foot of granite at 170 pounds and find that 1 cubic mile of the rock weighs 25,000,000,000,000 pounds. This is more conveniently written 25×10^{12} (10 to the

12th power.) Since we have to consider 200,000 cubic miles or 2×10^5, we have as the total weight of the granite in the Sierra Nevada the total of 5×10^{18} pounds. Stated in English numbers this is 5 quintillion pounds.

It is convenient to use as the unit of heat the British thermal unit or B.t.u., which is the amount of heat energy required to raise the temperature of 1 pound of water 1 degree Fahrenheit. If we were heating water it would require as many B.t.u.'s to raise the temperature of the mass 1 degree as we have pounds; but granite does not require so much heat. The specific gravity of granite is about 0.2 or one-fifth that of water. We thus have $\frac{5 \times 10^{18}}{5}$ or 10^{18} B.t.u.'s as the amount of heat energy necessary to raise the temperature of the granite mass 1 degree. Since we assume that it has been raised through 1,000 degrees, the total heat energy becomes 10^{21} B.t.u.'s, or 1,000,000,000,000,000,000,000 British thermal units.

This incomprehensible figure can best be understood, perhaps, if we transform it into mechanical work. How many miles, for instance, would this force raise the weight of the Sierra Nevada? Since 1 B.t.u. is equal to 778 foot-pounds, we can transform the above figure for the total energy into foot-pounds by multiplying. We thus have 778×10^{21} foot-pounds. Divide then by the weight of the Sierra Nevada granite in pounds and again by the number of feet in a mile, and the result would be the number of miles through which the energy would lift the granite mass, if it acted mechanically. It will be found that the total heat energy required to raise the temperature 200,000 cubic miles of granite, 1,000 degrees Fahrenheit would suffice to raise the weight of the mass 31 miles.

We are not yet done with this suggestion, for the granite has been heated up to the melting point only. It has not been melted. To accomplish that change it must absorb a very large amount of heat energy, corresponding to its latent heat of fusion. The measure of the latent heat of granite is indeterminate, because it consists of minerals whose latent heats are widely different and whose proportions vary; but it is at least 100 times as great as the pecific heat and may be 200 times as great. That amount of heats was contained in the molten granite when it rose into the outer skin of the earth.

The latent heat that the granite contained and gave off in cooling was enormous. We recognize that the Sierra Nevada is a young mountain range, and the extrusion of the granite with its contained energy was an event of a later geologic age. Evidently the earth is still charged with very large stores of energy. The action we have chosen as an illustration has been paralleled hundreds of times, probably thousands of times, during geologic history. The earth is majestically powerful. It inherited incalculable stores of energy as its substance gathered to form the globe, and it still retains enormous stores in spite of the losses that have been involved in the changes of a billion years or so.

FORMS OF ENERGY

Energy assumes various forms and does work in a variety of ways, according to the mechanism through which it acts. It is convenient for our present purpose to distinguish the forms of energy manifested in the earth as inertia, gravity, molecular and atomic energy, and heat energy.

Inertia.—Inertia is represented by the tendency of a body to persist in the state of rest or motion in which it is. It is omnipresent. When a body is at rest inertia may be regarded as potential. When a body is in motion it is an active force.

Gravitational Attraction.—Gravity is the attraction which the earth as a whole exercises upon all substance. It is the local attraction of the earth, the terrestrial manifestation of the universal force of attraction which exists between all masses in the universe. It follows the Newtonian laws in that the measure of the force is directly proportional to the square of the distance between two mutually attracting masses. We are accustomed to think of it as an attraction which draws all substances of the globe toward the center, which is the predominant fact. But it is also true that every part of the earth attracts every other part. A mountain range thus attracts a plumb bob and may deflect it from a true vertical to a measurable degree. A dense mass within the earth will similarly draw the plumb bob toward itself, away from a lighter mass at a similar distance. As we go from the surface toward the center of the earth, gravity increases, because radial distance to the center of attraction decreases. There is, however, a certain counterbalancing effect due to the mass above any level. That mass exerts an attraction upward, and the effect is to modify the rate of increase of the force of gravity. The consequence is that the attraction toward the center is a maximum at 610 miles (976 kilometers) below the surface. A ton of 2,000 pounds at the surface would there weigh 2,080 pounds. From that level downward the attraction diminishes and becomes zero at the center.

It is important not to confuse the force of gravity with its effect, the pressure of the load upon any buried mass. The force of attraction diminishes to zero at the center, as has been stated. The pressure increases from the surface to the center and is there a maximum.

The increase of pressure from surface to center is the increase in weight of the column that is supported. If the column were of uniform density from top to bottom the increase of pressure would be directly proportional to the length of the column, measured from the surface downward. But the density itself is greater at greater depths, partly because the materials are compressed, partly because the light weight surface rocks give way to denser rocks and these to still heavier iron, as stated in the previous chapter. The effect of compression was long regarded as adequate to produce the estimated density of the interior, and a law of pressure formulated by Laplace was accepted. The corresponding pressures, densities, and temperatures are given by Chamberlin,[1] as calculated by Lunn. These estimates are now replaced by the results of experiments by Adams and Williamson, which demonstrated that compression alone could not produce the required densities and consequently that heavier substances must constitute the inner earth.[2]

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[1] Chamberlin, T. C., and Salisbury, R. D. "Geology," pp. 564–566, 1909.

[2] Adams, L. H., and Williamson, E. D., The Composition of the Earth's Interior. Smithsonian Report for 1923, pp. 241–260, 1925.

The curves of density, pressure, and temperature deduced in accordance with this arrangement are given in their publication.

The accepted measure of the force of gravity is the effect it has at the surface of the earth in accelerating the velocity of a falling body. The rate of change of velocity or the acceleration thus imparted is found to be 32 feet (9.80 meters) per second in general, but it is subject to slight variations, either systematically with latitude on the earth's surface or locally according to the density of large rock masses beneath the surface.

The force of gravity is active when it acts upon a fallen body. It is said to be potential when the attraction acts upon a body which cannot fall. The potential energy is that which the body would develop in falling to the center of the earth and is therefore greater in direct proportion to the remoteness of the body from the center. It follows that the potential energy of the earth, so far as it results from the attraction of gravity, was greatest when the substance of the earth was distributed to the longest radius and is growing less as the globe condenses toward the center. The process of condensation by the movement of the mass toward its center may be regarded as having been continuous since the infancy of the nucleus, and is still continuing. In this process potential energy is converted into active gravitative force, and the latter in turn becomes heat energy. The conversion of gravity into heat is one of the most significant facts in the dynamics of the globe.

Atomic and Molecular Energies.—In dealing with the globe as a whole we have so far considered magnitudes of very great size. We now turn to examine the infinitely small, but immeasurably powerful, atoms and molecules.

The atomic and molecular energies constitute the mass of the earth. It would once have been considered more correct to say of these energies that they are stored in the earth, for we conceived that energy was something apart from matter and that it could be stored in matter. Matter without energy was inert substance. Energy was that which gave to matter the quality of activity, motion, life. But according to modern concepts, the atom is made up of particles of energy. Each particle of energy has *mass*, but it is not the inert, mechanical mass with which we are familiar through its weight and inertia; it is active, moving, electric mass. Matter is composed of such masses. It is, therefore, correct to say that the atomic and molecular energies constitute the mass of the earth.

We may recite the fact that an atom of any substance consists of a nucleus, which is a positive charge of electricity, and of electrons, which are negative charges of electricity. Electricity in this connection may be taken to mean that form of energy which is characterized by being either positive or negative and which reacts in such a manner that charges of like kind repel each other, whereas charges of opposite kinds attract each other. The effect of the attractions and repulsions in an atom consisting of the positive nucleus and negative electrons is to establish a balance of forces, which tends to assume and maintain a stable condition. The nucleus and the electrons remain firmly fixed in their attachments, even though they are in rapid motion, somewhat as the sun and the planets keep their relative distances. The stability of the atomic structure is obviously greatest in solids. It is to be noted, however, that the electrons are not all equally firmly attached to the nucleus, there being degrees of fixity among them, especially in the more complex atoms. Thus, the atomic structure may be altered by the removal of a relatively free electron or electrons.

Molecules might be described as compound atomic structures. A molecule also consists of a nucleus and attendant electrons, but the nucleus is composed of four or more positive charges, and the electrons represent two or more atoms. The system is in rapid motion, even in the firmest solid.

The possibilities of motion within an atom or molecule cannot be realized until it is understood that the structure of the system is as open as that of the solar system. In other words, the diameter of an electron is small compared to its distance from the nucleus as the diameter of the earth is small compared to its distance from the sun. The vacant spaces within an atom or a molecule are comparable on the atomic scale with the vacancies of space. The tiny masses of energy which are the planets of the atomic systems can therefore revolve and vibrate freely within the ranges of their mutual bonds.

Cohesive Force.—Cohesion, the bond of solid substances, is also interpreted as electrical attraction. It is regarded as the attraction between positive and negative charges in the peripheries of adjacent molecules or atomic groups. It varies according to the law of inverse squares of the distance between two centers, and is therefore greatly strengthened when they are pressed together or is correspondingly weakened when they are forced apart. It follows that the strength, rigidity, and elasticity of solids are increased by confining pressures, whereas they are reduced when pressure is relieved. These changes become very obvious when we add energy to a solid until we melt it or when we reduce the energy in a liquid until it solidifies. In these latter changes we say that we have raised or reduced the temperature by adding or subtracting heat.

Heat Energy.—Heat is described by the physicist as molecular energy. It is the energy of motion of the molecules or atoms. It is to be understood that two or more atoms revolve around their common center, and that the revolving system oscillates to and fro at great speed, even in solid substance. The energy thus involved in the system is partly fixed in the balance of the atomic structure and partly expressed in the momentum of vibration. The former is regarded as latent or potential. It can be increased by heating the substance or decreased by cooling it, and the effect is in the one case to drive the atoms farther apart, or in the reverse process to draw them together. In a similar manner and at the same time the momentum of the atomic systems is increased or decreased as the temperature is raised or lowered. Thus, if a substance is heated up the oscillations of the atomic sytems become more and more rapid and assume wider and wider swings. The pace can be speeded up to the point at which the intermolecular bonds are no longer able to maintain the solid state and the substance melts. The cohesion has then been broken down and the atomic or molecular systems move with relatively great freedom. In some rocks the failure of the bonds proceeds slowly through a wide range of temperature and the material passes through a pasty or viscous state, whereas in other rocks the transition from an elastic solid to a comparatively mobile liquid occurs in passing through a few degrees of temperature.

PRESSURE VERSUS HEAT

Pressure and heat are opposed forces that produce opposite effects upon substances. Thus, pressure reduces or tends to reduce volume. Pressure restrains atomic activity. Heat excites atomic activity. Pressure tends to retard or prevent those chemical reactions which involve an increase in volume and to promote those which are accompanied by a decrease in volume. Heat, on the contrary, tends to promote the former type of reaction and to hinder the latter.

In considering the contrasts suggested in the previous paragraph it is essential that certain distinctions be not overlooked. By pressure, as the word is there used, we mean *confining pressure*; that is, a pressure from all sides and equal on all sides. Thus, the air exerts a confining pressure upon a balloon, and when the balloon does not change its volume that confining pressure is exactly balanced by the tendency of the gases within the balloon to expand. Or water exerts a confining pressure upon a submerged sphere and that pressure is resisted by the force which the substance opposes to compression.

In both of these illustrative cases there may or may not be *differential pressure.* If the air is heavier than the balloon it exerts an upward lifting force upon the balloon. The lifting force is a differential pressure corresponding to the difference in weight of the gas within the balloon and an equal volume of air (if we neglect the weight of the envelope). Similarly, there will be a differential pressure exerted upon the sphere in water, provided the sphere be lighter or heavier than water. In each case the differential force is an effect of gravity and depends for its amount upon the difference in the specific gravities of the immersed body and the surrounding medium.

Confining pressure does not produce motion. Differential pressure may or may not produce motion. In the examples of the balloon and the submerged sphere motion is suggested because we are accustomed to see balloons rise and bodies in water either rise or sink. But a balloon will come to rest at a height at which it weighs no more than the volume of air which it displaces, and the like result will appear if the submerged sphere has the same specific gravity as the liquid in which it is immersed. Differential pressure may also fail to cause motion because the substance on which it acts resists adequately. For instance, air bubbles move very slowly or not at all in molten glass. The glass offers relatively great resistance to their movement as compared with the lifting force exerted upon the light bubbles, even though the difference of specific gravity between the air and the glass is considerable.

Differential pressure is not necessarily an effect of gravity, as it is in the cases used for illustration. Any directed pressure may be a differential pressure, provided it is greater than pressures from other directions. The cause of it may be an unbalanced weight or an unbalanced stress from any source whatsoever. The essential fact is that there is a difference among the stresses from different sides and that this difference disturbs the balanced condition which is characteristic of confining pressures.

On a previous page, in contrasting the effects of pressure and heat, the antithesis referred to confining pressure only. Differential pressure acts to promote heat effects. It weakens atomic attractions and aids heat in facilitating chemical reactions. It transforms latent heat into sensible heat and raising the temperature contributes directly to the heat effects. Differential pressure and heat thus cooperate to bring about changes, whereas confining pressure acts to maintain stability.

The relative effects of pressure and heat upon rocks are well known, within the range of the moderate intensities which we can reach in our laboratories. The possibilities of experimental investigation are, however, limited by the fact that steel containers, which are used to confine substances and may be subjected to very high pressures so long as they are cold, weaken when heated. We cannot approach the conditions of great pressure and high temperature which exist within the earth and there oppose each other in determining the volume, crystalline form, and solid or liquid state of rocks. Our speculation as to the restraint placed by pressure upon the activity stimulated by heat may be guided by knowledge a little way, and thereafter must depend upon following the given direction.

The action of heat upon rocks is to weaken them. It may change their state from solid to liquid, when the action is sufficiently intense, or produce other changes in them when it is less intense. Confining pressure opposes these changes. If we think of pressure as constant while heat energy varies we know by observation that rocks will respond to the variation in energy. They will expand, recrystallize, or melt with rising temperature, or reverse these responses with falling temperature.

If temperature remains constant changes of confining pressure produce characteristic effects. An increase reduces volume and increases density. Increased pressure also increases the resistance which solids oppose to distortion, makes them stiffer and stronger. This fact should be noted, because there is a common impression that pressure may make rocks " plastic," i.e., soft.

A decrease in pressure with constant temperature means an expansion of volume, a weakening of stiffness and strength, and possibly melting, provided that the temperature be high enough.

It is well known that the temperature of any substance is raised if it is compressed, and that the temperature is lowered if the substance expands. That is to say, temperature and pressure are so related that one cannot change without some equivalent variation in the other. The theoretical proposition that either may be changed while the other remains constant assumes that there is a compensating loss or gain which maintains the constancy. Thus, increasing pressure may be accompanied by a loss of heat due to some cooling mechanism, which removes the energy that would otherwise appear as increased temperature. In geologic speculation we deal with conditions within the earth, where cooling mechanisms are inefficient or non-existent. A change from lower to higher pressure on any mass is therefore accompanied by a rise in temperature, unless some unusual circumstance reverses the conditions. On the other hand, a release of confining pressure would cause expansion of the rocks and a fall of temperature, which would cause a flow of heat from adjacent masses. Since variations of pressure within the earth are generally very gradual and the conductivity of rocks is very small, such changes must be exceedingly slow in developing and the restoration of equilibrium must require a long time. The exceptional case in which pressure and temperature may be subject to relatively rapid change occurs in the movements of melted masses. Even they must move slowly, as a rule, except when erupted at the surface. We may conclude, therefore, that the reactions of heat and confining pressure upon each other have usually attained a balance that is disturbed only by exceedingly slow changes during very long periods of time. This is a prime condition of the stability of terra firma.

STATES OF MATTER

The effects of heat and pressure depend not only upon their mutual reactions but also upon the resistances offered by the rocks. The resistances in turn depend upon the physical state of the rock, whether solid or liquid, crystalline or glassy, refractory or fusible; and also upon its adaptation in chemical constitution and crystalline form to resist the forces that bear upon it. Illustrations of these contrasting conditions will readily occur to the student, who can place them in their proper relations to conditions of high or low temperature and high or low pressure.

In order, however, that the thinking on these subjects should be free from misconceptions, it is desirable to define certain ideas that we describe by words which are often used in more than one sense. What do we mean by solid or liquid? How are they to be contrasted?

A solid resists distortion and, if forced out of shape within certain limits, will recover its original form. Liquids also resist distortion, but will not recover from it. Hence we say that a solid exhibits elasticity when distorted, whereas a liquid does not. This is a fundamental distinction, and it is the basis of the conclusion that that portion of the globe which transmits elastic, transverse waves from any earthquake focus is solid.

Solids are firm; liquids are mobile. Solids break; liquids flow. These are distinctions that we observe, but they are not universally true. There are conditions under which none of the four statements is true. Solids cease to be firm when pressed beyond their power of resistance; they cease to break when under a sufficient confining pressure. If pressed beyond their power to resist while at the same time subjected to a sufficient confining pressure, solids flow without breaking. Firmness is relative, and breaking or flowing are modes of change of form which depend upon environment.

Liquids are not mobile under all conditions. They share with solids the capacity to resist a change of form, or, as it is said, they possess *viscosity;* and this capacity is greatly increased by confining pressure, in a manner similar to the effect of such pressure in increasing the strength of solids. Gasoline, for instance, may be cited as an exceedingly mobile liquid as we know it, but Bridgman has raised its stiffness, that is its viscosity, to that of vaseline by placing it under uniformly confining pressure of 180,000 pounds to the square inch at 0° C.[1] It is apparent that molten rock, although liquid, must possess very high viscosity when confined under the great pressures that exist within the earth.

The word viscosity is used in the preceding paragraph in the technical sense given it by physicists, to represent resistance to distortion, not ease of motion and change of form. Viscosity corresponds with stiffness, and the higher the viscosity the stiffer the resistance to flowing.

Viscosity is a resistance that involves the factor of time. Glass is a substance that offers a good illustration of that fact. If a rod of glass be suspended in a horizontal position, it will sag and will continue to sag indefinitely under the slight stress of its own weight. When relieved of that stress it will not recover its former shape. Yet, if we had applied the same slight stress quickly and had then released the rod, it would have vibrated to and fro as an elastic body. A substance which changes form in response to a long-continued stress, however small, and which does not return elastically is a liquid. Having this character, glass is a liquid, in spite of the fact that it has many of the properties of a solid, especially that of elasticity in response to a quickly applied stress. Glass is called a *viscous liquid*, the term viscous meaning that both time and stress are involved in the manner of deformation which it may suffer. Thus, glass may react to stress in any one of four ways: to a quick stress within the elastic limit it responds elastically; to a prolonged stress within the elastic limit it yields by flowing; to a stress beyond the elastic limit it reacts by breaking, unless so confined that it cannot break; and if so confined it will flow as solids flow, by shearing.

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[1] Bridgman, P. W., *Proceedings* Amer. Academy of Arts and Sciences, vol. 61, pp. 57–98, 1926.

Viscous resistance contrasts with rigid resistance to deformation. The latter is characteristic of solids and is the resistance that they offer to deformation within the elastic limit. It is closely related to elasticity. Steel, for instance, is a rigid and very elastic solid. Time does not affect its response to stress. A small stress will deflect a steel rod immediately, to the extent permitted by the elastic resistance but no further, no matter how long it may be maintained. If it be removed the rod springs back. The steel has not taken a set; it has not flowed as a viscous liquid would; and yet steel can be made to flow if it be properly confined and subjected to sufficient differential stress.

The distinction between viscosity and rigidity plays a very important part in geologic theory. It is well established that the earth is very rigid. It resists the attractions of the sun and moon, for instance, as strongly as if it were strong as steel or stronger. These attractions pass quickly and the response of the earth is that of a rigid, highly elastic body. It is equally well established, however, that the earth yields slowly to the forces that raise continents or that cause similar changes of form. These slow movements unquestionably resemble flow in that they take place without producing fractures. But what kind of flow is it? The flow of a viscous liquid like glass, which takes place in response to small stresses continuously applied during the millions of years? or solid flow like that of steel, which is conditioned by adequate confining pressures and requires very great deforming stresses? or some form of flow resulting from recrystallization, through the action of molecular forces stimulated by heat energy? The attempt to answer these questions has led to several different theories of the forces that produce continents and mountain ranges.

SUMMARY REGARDING FORCES

Moment of Rotation.—This force determines the spherical form of the globe and develops the centrifugal pull in consequence of which the equatorial diameter is now about 27 miles (43 kilometers) longer than the polar diameter. The moment of inertia of rotation is enormous. Any force which might change it must act through a very long time to produce a gradual and relatively small effect. A force adequate to produce a sudden change in the rate of rotation or in its direction would alter the surface of the globe beyond recognition. This fact bars theories of the displacement of the poles.

Gravity.—A persistent attraction, definite and invariable in direction, omnipresent and unceasing; constant for any given mass in a fixed position, so long as the rate of rotation of the earth is constant; varying as the densities of different masses and inversely as the distance to the center of attraction; attracts most strongly at 610 miles below the surface and diminishes to zero at the center.

Gravitative Pressure.—An effect of gravity, equivalent to load; varies directly with the intensity of gravity, the density of superincumbent material, and the depth below the surface of the earth; amounts to 1 atmosphere at the surface of the ground and 3,000,000 atmospheres at the center.

Volume Elasticity.—A resistance offered by solids, liquids, and gases to volumetric compression, and also a force exerted to cause expansion of matter within narrow limits for solids and liquids, but without limit for gases.

Distortional Elasticity.—A resistance offered by solids to distortion and by virtue of which they tend to recover from distortion within the elastic limit; closely related to rigidity, which is the degree of resistance that a solid in permanent equilibrium opposes to stresses tending to change its shape.[1]

Rigidity.—See distortional elasticity.

Viscosity.—A resistance offered by liquids to flowing; the more viscous the liquid the greater the resistance. Viscosity is increased by confining pressure; it is overcome when flow is caused by differential pressure.

Atomic and Molecular Energies.—It is conceived that matter consists of atoms which are organized as molecules, and of molecules which in turn are organized in some manner that determines the characteristics of the substance. The organization is determined by attractions and repulsions in obedience to which the molecules revolve about centers and vibrate to and fro with reference to some mean position. The energy involved in these motions is capable of doing work, as when one molecule collides with another or a large number of molecules strike a neighboring group over a surface. In such work energy is imparted from one molecule or group of molecules to another, the distribution of energy in the system is changed and the form of energy may be altered, as when heat is produced or becomes latent. It is established that the organization of any molecule or atom depends upon the maintenance of conditions of temperature and pressure within limits that vary for different substances, but that a sufficient change of conditions will cause the molecule or atom to undergo a change of organization in consequence of which energy is either given off or absorbed. The atomic and molecular energy which may thus be exchanged or transferred is very great and very pervasive, since it is the actual substance itself. We are accustomed to think of it as capable of producing very great effects; we should also remember that the balanced systems in which it exists in rocks are correspondingly stable.

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[1] Becker, G. F., Finite Homogeneous Strain, Flow, and Rupture of Rocks. *Bull.*, Geol. Soc. America, vol. 4, 1893, pp. 44–48.

Heat.—Long regarded as a fluid, heat is now recognized as molecular motion. Since it can be imparted from one molecule to another, it is capable of flowing through substances and may appropriately be described as fluid energy. Heat gives rise to temperature, which rises when the velocity of vibration of the molecules is speeded up or falls when that velocity falls off. A transfer of heat from one substance to another is accompanied by changes in both, and these changes may go so far as to alter the state of either, as when the one substance melts while the other loses heat.

If now we review these forces and resistances with a view to seeing what part each by itself or any of them in combination may play in geologic processes, we may distinguish those that make for stability from those that tend to effect changes. On the one side stand the moment of inertia of rotation, gravity, rigidity, and viscosity, and the atomic balances, all tending to keep things as they are or to permit only very gradual alterations of the status quo. Opposed to these conservatives is heat, the disturber of the established order.

CHAPTER XVIII

ZONES OF PRESSURE, STRENGTH, AND TEMPERATURE IN THE OUTER CRUST

Radial structures; radial conditions. Spherical structures; spherical conditions. Effect of confining pressures. F. D. Adams' experiments on strength under pressure; results obtained. Relation between strength and load; which increases faster? The distinction between absolute strength and relative strength; the factor of safety. At what depth does the factor of safety reduce to one or less than one? Depth of the "zone of flow." Experiments by Adams and Bridgman; conclusion. How overloaded rocks behave; association of shearing and flowing in plastic substances. Plasticity a mode of distortion, not an indication of resistance to distortion. Heat, its influence in modifying strength. Zones of temperature; sources of heat; residual heat of a molten globe; heat due to compression; atomic and molecular reactions as a source of heat; radio-activity; strain as a source of heat. Distribution of heat; alternative theories and estimates; distinction between the results of theoretical estimates and the facts; the globe homogeneously layered or heterogeneously massed? The core, the stereosphere, the asthenosphere, and the crust.

HYPOTHETICAL COLUMNS OR SHELLS

The earth being nearly spherical it is possible to think of its solid mass, or of that portion of its mass which is solid, as composed either of radial pyramids or of successive shells, and neither concept need exclude the other.

For instance, let us assume that the globe is composed of radial pyramids, each one being of square cross-section and in contact with its four neighbors. The pyramids will form the whole spheroid, if each lies with its apex at the center and its base in the surface of the earth. Each one will then have the height equal to the radius, approximately 4,000 miles (6,400 kilometers) and we may arbitrarily postulate that each base has an area equivalent to 1 square mile (2.59 square kilometers). Their number would then be nearly two hundred million (196,940,700). About one-fourth of the bases would constitute the areas of the continental plateaus, the other three-fourths would form those of the ocean bottoms and continental slopes. This imaginary radial structure is convenient when we seek to picture the distribution of vertical forces and vertically arranged conditions; as, for instance, if we discuss the effects of gravity upon columns of different densities and the conditions of support of the columns. The picture is, however, merely a convenience; it does not represent a natural structure.

On the other hand, it is convenient to consider a globe as made up of successive shells, each one of greater or less thickness arranged around a central core. The concept is one of common occurrence in geologic writings, as when mention is made of the lithosphere, the zone or shell of fracture or of flow, or of a hypothetical basalt shell. In all cases the idea is that there can be distinguished everywhere in the earth a shell, which is limited above and below by recognizable changes of material or of conditions. Thus, the lithosphere is conceived to be a shell of crystalline rock, which rests upon something different below and is in contact with the atmosphere and hydrosphere above. The outer crust was long regarded as a shell of cold, rigid rock that floated on a molten core and, although that view is no longer tenable in its original form, we do recognize that there is an external shell in which the strength of rock is very great as contrasted with the weakness induced by high temperatures at greater depths. The idea that the earth is composed of concentric shells is easy to grasp and it affords a convenient picture for discussion; but we should not fail to remember that it is as artificial as the concept of radial pyramids. The real structure of the deeper masses within the globe may be as heterogeneous as the distribution of rocks on the surface.

The existence of the lithosphere is, however, well established. It is recognized as a shell of rock, predominantly crystalline, silicate rock, enveloping completely the interior body. The latest speculations indicate that it is probably 2,000 miles (3,200 kilometers) deep (see Chap. II). It is therefore reasonable to assume that we may take as a starting point for discussion of conditions within the earth the characteristics of rocks as we know them at the surface. The obvious ones are weight, strength, and reactions to temperature changes.

EFFECT OF CONFINING PRESSURES IN THE EARTH

We may introduce the study of confining pressures within the earth by considering the effect of load upon rocks regarded as foundations which support the superincumbent weight. Any column of rock measured from the surface downward may be considered as load and the rock immediately below it as its foundation. Such a column is part of the hypothetical radial structure that has been suggested and is in contact with all adjacent columns. If all columns are assumed to be of uniform depth they will constitute a shell of uniform thickness. Since the foundation rocks at any considerable depth are under approximately the same load and cannot escape laterally, the pressures are confining pressures; that is, they tend to compress the rock from all sides about equally.

By reference to the values given in the preceding tables the student may observe that a column of rock of average density and between 3 and 5 miles high, according to the strength, will crush its foundation rock, *provided the latter be no stronger than it is at the surface.*

That rock grows stronger if confining pressure is increased was first suggested by G. K. Gilbert about 1890. Frank D. Adams first proved it experimentally.[1] Adams' experiments consisted in determining the crushing strength of granite, marble, and other rocks when confined in a steel jacket which exerted a known, but not irresistible confining pressure. The specimens tested were in the form of cylinders, which were bored from selected rock, turned, polished, and finished to precise dimensions (1.58 inches or 4 cms. long and 0.79 inch or 2 cms. in diameter). The steel jackets were fitted so closely to the cylinders that the rock was supported on all sides and could yield under compression only by bulging the steel wall. Pressure was applied at the ends of the cylinders to produce this effect. The thickness of the steel wall was 0.25 cm. in one series of experiments and 0.33 cm. in another set. It was found by experiment that the resistance offered by the thinner wall was equal to the confining pressure which would be exerted by adjacent columns of rock 4.2 miles (6.76 kilometers) high, while that of the thicker wall was equivalent to the confining pressure under similarly placed columns 5.8 miles (9.34 kilometers) high. That is to say, the confinement of the specimens was that which is maintained on all sides of rocks buried 4.2 miles or 5.8 miles in the earth.

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[1] ADAMS, F. D., and BANCROFT, J. A., On the Amount of Internal Friction Developed in Rocks. *Journal of Geology*, vol. XXV, pp. 597–637, 1917 (636–637).

Under these conditions the test cylinders were compressed to the form of flattened, but still firm solid discs. Adams states the results obtained as follows:

> Thus at these respective depths the additional tangential thrust required to induce a pronounced movement in the case of marble and granite, respectively, would be as shown in the following table.

	At Depths of 4.2 Miles		At Depths of 5.8 Miles	
	Pounds per Square Inch	Atmospheres	Pounds per Square Inch	Atmospheres
Marble.	66,400	4,517	74,500	5,068
Granite.	138,500	9,422	159,600	10,857

Adams' experiments were conducted on a number of different rocks and his general conclusions are expressed as follows:

> 1. All the rocks employed in the present investigation can be deformed under differential pressure at ordinary temperatures.

2. In order to effect equal deformation, it is necessary to employ differential pressures having different values in the case of several rocks.

3. The ease with which these rocks are deformed has as one of its functions the hardness of the rock (or of the minerals composing it.)

4. In the case of the softer rocks—alabaster, steatite, marble, etc.—the deformation is produced by movements due to a slipping within the constituent crystals of the rock on their gliding planes, often accompanied by twinning, the movement in this case being similar to that seen in metals when they are deformed. In the harder rocks the deformation is accompanied by granulation, the texture being similar to that found in mylolite. (This effect is that which is described by Van Hise as "mashing." See A Treatise on Metamorphism, pages 760–764.)

5. Each of the softer rocks at least has a well-defined modulus of plasticity.

6. The "work done" when a rock is deformed by tangential thrust, within the earth's crust, increases rapidly with the weight of the superincumbent strata, i.e., with the depth below the surface.

7. The relative ease with which the several rocks will flow under differential pressure is shown in the following table, which gives mathematical expression of the "work done" in deforming standard columns of each rock.

RELATIVE AMOUNT OF "WORK DONE" IN EFFECTING AN EQUAL DEFORMATION IN UNIT COLUMNS OF DIFFERENT ROCKS.

	Under Resistance of			
	0.25 cm. Steel Tube		0.33 cm. Steel Tube	
Steatite	26,054	0.50*	34,123	0.56*
Alabaster	35,569	0.69	42,946	0.71
Sandstone	41,262	0.80	53,446	0.88
Marble	51,708	1.00	60,415	1.00
Dolomite	66,362	1.28	77,092	1.28
Belgian Marble	73,754	1.43	79,362	1.31
Slate	79,069	1.53	97,154	1.16
Diabase	92,985	1.80	107,431	1.78
Granite	104,169	2.01	119,877	1.98

* In this column the "work done" is calculated on the basis of marble as unity.

8. A uniform thrust exerted on a prism of the earth's crust may deform and fold the upper portion of the mass, while it will be quite insufficient to produce any movement in the lower part of the same mass.

9. The thrust required to develop deformation, taking no cognizance of the influence of heat or the time effect which might result if the pressure were applied with extreme slowness, in the case of marble and of granite, is shown by the values given in the table.

10. Reverting to the question propounded by Dr. Gilbert, in order to develop flow in any rock within the earth's crust the rock must be submitted to a differential stress which is greater than that which is required merely to break down its texture and very much greater than that which is sufficient to crush it to pieces under the ordinary conditions which obtain at the surface of the earth.

The results of Adams' experiments, stated above, indicate a condition of enormous strength and rigidity which is greatly in excess of that commonly believed to exist. Strength is, however, always a relative term. In this case the strength of rock at any depth may be compared with the load that the rock at that depth supports, and the question may be asked whether the strength is always the greater of the two. In other words: does the increment of strength keep pace with the increment of load as the depth below the surface increases? The question is answered in a way by the data supplied by Adams' experiments. Thus:

Depth, Miles	Strength Rock, Miles High	Load	Ratio Strength to Load
0	5*	0	
4.2	21.6	4.2	5.0
5.8	23.3	5.8	4.0
9.0	25.8	9.0	2.8

* Strength is expressed in terms of a column of rock which would exert at its base a pressure equivalent to that determined by experiment to be the crushing strength of the rock under the stated load. A column of rock 1 mile high exerts a pressure of 6,400 pounds per square inch.

When thus tabulated the data show that rock at a depth of 4.2 miles is 5 times as strong as it need be to just support the load of

4.2 miles which rests upon it, whereas at 5.8 miles below the surface the ratio has diminished to 4. At what depth will the ratio diminish to 1? At what depth to less than 1?

An attempt to answer this question by putting the available data into a curve was made by Bailey Willis in 1920. In the diagram, Fig. 150, let the curve *LMNP* represent the strength of rock as stated in the preceding table, and let the prolongation of the curve through *Q* and *R* be regarded as a reasonable, though theoretical extension of it. The abscissas of this curve represent the strength; the ordinates represent the load. Therefore, the point

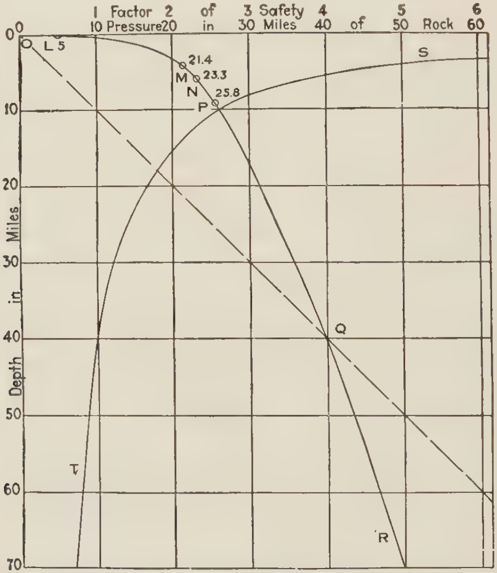

FIG. 150.—Comparison between the actual strength of granite and the load on it at different depths in the earth's crust.

The curve *LMNPQR* represents the crushing strength in miles of rock. The broken line *OQ* represents the actual load. The ratio between the two, or factor of safety, is shown by the curve *ST*. At a depth of 40 miles, at *Q*, the load equals the crushing strength, and the factor of safety is 1. At greater depths the rock is potentially crushed.

where the curve cuts the 45-degree line on which abscissas and ordinates are equal gives the depth at which the strength and load are equal.

The diagram contains a second curve, *SPT*. It is obtained by dividing the absolute strength of the rock (as determined by experiment or as inferred beyond the range of experiment) by the load. It therefore expresses the relative strength. In engineering the value obtained by dividing the absolute strength by the actual load is called the *factor of safety*. So long as the factor of safety is considerably more than 1, the structure is relatively strong; as the factor of safety approaches the value of 1 the structure is regarded as weak; and if the ratio becomes less than 1 the structure will fail unless it is bolstered up. The curve *SPT* shows that the factor of safety for rocks reduces to 1 at a depth of 40 miles, on the assumptions made in drawing the diagram. Below that depth it is less than 1. The structure would therefore fail if the columns of rock did not mutually bolster each other up by lateral pressure.

If, under these circumstances, the lateral pressure were relaxed, the load would cause shearing and displacement, but in so doing it would have to overcome the absolute strength of the rock, which is a real quantity, as we see by the curve *LMNPQR*. This conclusion contradicts the idea that pressure alone can make rocks weak or soft. They behave mechanically like plastic substances, but they are not easily molded in the sense that our experience with wax or putty suggests.

DEPTH OF THE ZONE OF FLOW

The depth in the earth at which the strength of the rock is just equal to the load that it supports is the utmost depth at which any empty cavity can continue to exist. Several estimates were made of that depth before it was determined by experiments. Van Hise,[1] aided by the mathematical studies of Hoskins, reached the conclusion that:

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[1] Van Hise, C. R., Principles of North American Pre-Cambrian Geology. U.S.G.S., *Annual Report* 16, Pt. 1, p. 593, 1894–95.

> It appears highly probable that at a depth of 10,000 meters (33,000 feet or about 6 miles) not only do no crevices exist permanently in the earth, but the rocks are in such a condition that actual welding of the fractured parts would soon take place, supposing fracture to occur.

This conclusion was generally accepted and has exercised an unfortunate influence upon theories of displacement, since it indicated that a zone of " flowage " or easy movement exists at very moderate depth. We have but to consider that at six miles below the surface the rock is about four times as strong as it need be to support the load, in order to recognize the fallacy of that inference.

Adams' experiments to determine the strength of rocks under confining pressures have been described. He also made others to ascertain at what depth cavities would close. He compressed cylinders of limestone and granite, in which millimeter holes had been drilled and which were enclosed in unyielding steel jackets. Pressure, applied at the ends of the cylinder, was raised until the hole transverse to the direction of compression was flattened, or the hole parallel to the direction of compression was filled with splinters, or both holes were thus filled. Some of the experiments were carried out at ordinary, " room " temperatures, others at the highest temperature permitted by the steel jackets, which tended to soften. The periods during which the pressure was maintained in different tests varied from 70 seconds to 2.5 months. Some of the results are listed in the following table. For full discussion the original articles should be consulted.

From the results obtained at room temperatures it appears that limestone would collapse at a depth of 20 miles, whereas granite would not fail until a depth of 31 miles was reached. At the temperature of 450 degrees C. neither limestone nor granite failed under a pressure equivalent to a depth of 15 miles; but the limestone gave way at about 500 degrees C., probably because of chemical decomposition of the calcite.

Bridgman made experiments on the closing of openings in rocks, which supplement those of Adams in an instructive way. In explanation of his purpose Bridgman says: [1]

> The most obvious criticism of these (Adams) experiments is that the manner of applying the stress is such that its character cannot be at all precisely specified, since the blocks were enclosed in shrunk-on jackets of mild steel, which yielded as the block was distorted.

Depth of Closure of Openings in Rock

Kind of Rock	Temperature	Pressure		Equivalent Depth, Miles	Duration of Experiment	Effects, *T* transverse hole *P* parallel hole
		Pounds per Square Inch	Kilos per Square Cm.			
Limestone	Room	96,000	6,750	15	2.5 mos.	No movement
Limestone	Room	128,000	9,000	20	2.5 mos.	*T* smaller, *P* partly filled
Limestone	Room	193,000	13,570	30	7 hrs.	*T* unchanged, *P* partly filled
Limestone	Room	200,000	14,060	31	0.5 hr.	*T* flattened, *P* partly filled
Limestone	450C.	64,000	4,500	10	7 hrs.	No movement
Limestone	450C.	96,000	6,750	15	70 secs'	Slight movement
Limestone	490 to 513C.	96,000	6,750	15	70 hrs.	*T* closed
Granite	Room	128,000	9,000	20	2.5 mos.	No movement
Granite	Room	199,000	13,990	30.86	15 hrs.	No movement
Granite	Room	200,000	14,060	31	2.5 mos.	*T* unchanged, *P* partly closed
Granite	Room	225,000	15,640	35	2.5 mos.	*T* filled, *P* largely filled
Granite	550C.	96,000	6,750	15	70 hrs.	No movement

In order to avoid misunderstanding, it is desirable to note that Adams states " the rock was firmly held on all sides by the steel." The yielding to which Bridgman refers was within the elastic limit of the steel and is not to be confused with the distortion of the thinner steel tubes employed by Adams when he compressed cylinders to discs and bulged the tubes.

[1] Bridgman, P. W., The Failure of Cavities in Crystals and Rocks under Pressure, *Am. Jour. of Science*, 4th series, vol. XLV, pp. 243–268, 1918.

Bridgman continues:

> In an attempt to avoid this element of ambiguity I repeated the experiments of Adams under conditions such that the stress could be precisely specified. The cylinders of rock containing a cavity were directly immersed in a liquid, and stress applied by subjecting the liquid to high hydrostatic pressure. The collapsing stress so obtained was considerably lower than that of Adams.

Bridgman tested a variety of crystals and rocks, but only the experiments on granite and limestone were similar to those of Adams. With both rocks a pressure of 5,000 kilos per square centimeter (71,115 pounds to the square inch) was applied for an hour at room temperature, and the hole in the specimen was found to be filled with splinters from the walls. The failure occurred at some pressure below the maximum applied, but the method did not permit it to be determined. There is, however, a great difference between 5,000 kilos or less obtained by Bridgman and 14,000 determined by Adams. The explanation lies in the fact that the resistances in the two sets of experiments were as differently oriented as the pressures. In Adams' experiments the strength tested was that of a column compressed longitudinally and so supported around its exterior that it could fail only by shearing toward the center. In Bridgman's experiments the strength tested was that of a thick-walled tube crushed transversely. The latter would in all cases offer much less resistance. Failure would occur transversely under much lower stress than would be required to cause shearing longitudinally and inwardly. The application of longitudinal stress by Adams determined that shearing must occur in a direction in which resistance was high. The application of hydrostatic pressure by Bridgman determined that the specimen should yield in that direction in which it offered the least resistance.

Bridgman's results demonstrate that a cavity which is of weak form or which is situated so that its least resistance is in the line of major stress may collapse at depths of 12 miles (20 kilometers) and very probably at even less depths. Adams' experiments show that minute cavities which are more favorably conditioned may remain open at depths nearly or quite as great as 30 miles (50 kilometers).

HOW OVERLOADED ROCKS BEHAVE

Movements in the Zone Flow.—It follows from what precedes that rocks below thirty miles in depth below the surface of the earth, and in many cases at less depths, are exposed to confining pressures that are greater than their crushing strength. They are *potentially crushed:* being strongly compacted, the particles or crystals cannot separate; if they are forced to move on each other they do so in intimate contact, without opening any spaces. The movement thus partakes of the character of flowing.

Since movements in the depths of the earth occur as if the solid rock flowed, the zone below the zone of fracture has been called the *zone of flow.* This is not a well-chosen name for it conveys the idea that the rock yields easily, like a fluid, which is not the fact. It is necessary to emphasize the point to avoid the misconceptions that follow from the idea of fluidity or mobility.

So long as it has not been melted crystalline rock remains elastic and rigid, no matter to what degree overloaded and confined. That is, it retains the characteristics of a solid. The transmission of elastic, transverse waves from earthquake shocks proves that this is the physical state of the earth's substance down to 2,000 miles (3,200 kilometers) below the surface.

An overloaded solid, which is not heated to the melting point, will shear like a solid if subjected to sufficient additional unbalanced pressure, yet will flow into an opening if sufficiently relieved of confining pressure.

The possibility of the association of the two modes of deformation, shearing and flowing, in the same substance under excessive load and unbalanced pressures, was demonstrated by Bailey Willis in experiments on the distortion of models designed to illustrate folding.[1]

The models consisted of layers in which wax was the principal constituent, but which were made harder or softer by the addition of other substances. In certain cases the mixture was such that it had the consistency of butter at 70 degrees Fahrenheit or of stiff vaseline. It was placed under a load of 5 pounds to the square inch, which caused it to spread and press against the sides of the box in which it was confined. The model was then compressed by causing a piston to advance against it. Two effects were noted: at first the model sheared like a rigid solid along well-defined and precisely oriented shearing planes; but it also spread and pressed more strongly against the sides of the box. One side was of plate glass, which presently broke. The butter-like substance instantly shot out through the cracks, forming thin sheets, no thicker than heavy paper, which nevertheless stood out an inch or more in front of the glass.

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[1] Willis, Bailey, Mechanics of Appalachian Structure, U. S. Geol. Survey, *Thirteenth Annual Report*, 1893.

This illustration introduces the suggestion that overloaded crystalline rock behaves like wax, and the comparison is not inappropriate. Under the stated conditions both substances are weak solids *when considered with relation to the pressures and deforming forces*. But the weakness is relative, not absolute. The wax was weak in comparison with stresses easily imposed under experimental conditions. The rock would have been exceedingly strong under those same conditions. But if we put the rock under conditions of the same kind and subject it to great stresses that similarly exceed its resistance to deformation, it will change form in a similar manner.

Wax is a type of *plastic* substances. The term plastic may be applied to overloaded rocks to describe the manner of deformation they can undergo, provided that its significance be restricted to the manner of deformation and that the implication of ease of distortion be deliberately and consciously set aside as false.

The preceding estimates of strength are to be qualified by introducing the factor of heat. Adams' experiments were carried out at temperatures at which the rock was not materially affected. Had it been possible to raise the temperature as well as the pressure, the strength would have been correspondingly lowered. The influence of heat is not very marked, however, down to the depth of 40 miles, and probably does not raise the level at which strength and load are equal for the strongest rocks more than 5 miles. That is, the factor of safety becomes 1 at a depth of 35 instead of 40 miles, on the assumption of the original estimate.

Compression due to confining pressure and expansion due to rise of temperature are opposed. The one forces the molecules closer together, the other spreads them apart. Both pressure and temperature increase with depth. Their relative effects depend on the relation of their rates of increase, and it is possible to assume that rocks might become denser through excess of compression, or might remain unchanged in volume because of a balance between compression and expansion, or might grow lighter on account of a more rapid rise of temperature.

It is regarded as well established that there is an increase of density from the surface downwards in the earth and consequently that the effects of confining pressure overcome those of rising temperature, under normal conditions. Compression normally controls expansion, but compression and expansion wrestle with one another in constant and unrelaxing opposition. If pressure lessens, expansion instantly ensues. If temperature falls, compression immediately takes place. The rock responds at once to the slightest change in the conditions of its environment by a corresponding change in volume.

Although, at least to a depth of half the earth's radius, the normal rise of temperature is inadequate to overcome the effects of the more rapidly growing pressure, there are exceptional developments of high temperature which do offset pressure and result in momentous reactions. The cause of these special conditions is a matter of hypothesis.[1] It may be any condition by reason of which heat energy accumulates to a degree sufficient to cause recrystallization or melting. In consequence of these effects it then becomes latent, and in the case of melting may be carried out by the extrusion of the molten mass. The condition of peculiarly high temperature is thus both local and temporary, and in this respect the hypothetical occurrence corresponds with that which is demanded by geologic evidence of variations in the activity of mountain growth and volcanoes.

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[1] Chamberlin, T. C., and Salisbury, R., "Geology," vol. 1, pp. 559–569, 1909.

ZONES OF TEMPERATURE

Sources of Heat—In the uncertainty of our knowledge there can be little unanimity of opinion among geologists and astronomers regarding the sources and distribution of heat in the globe. Something depends on the origin of the planet; more depends on the manner of consolidation; and whatever the initial supplies may have been, a great deal depends upon the manner of dispersion of heat, which determines its actual distribution.

The molten globe (if it ever was such) lost much of its inherited heat energy by radiation and cooled on the outside. This being the assumption, it is commonly thought that the central portion of the sphere may have remained molten, since the conduction of heat through a thick shell of rock would represent an inappreciable loss, even in many millions of years. Kelvin and Jeffreys have shown, however, that a solidified crust, being heavier than the melted rock beneath it, must break up and sink. It would therefore form a solid core and the globe would become a honeycombed solid with cells still filled with liquid.[1] It does not appear that Jeffreys, from whom this last statement is taken, considered the probable duration of the existence of such a honeycomb. The solid rock surrounding the liquid in the cells could not be rigid enough to retain its form when once it had structural continuity. The stresses transmitted through it would squeeze it together and would force the liquid out of the deeper cells toward the surface. Complete solidification would ultimately result. The process of solidification would involve a certain amount of compression by gravity and consequently would produce heat in the interior, some of which would raise the temperature of the residual magma and pass out with it, while a remainder would be held within the poorly conducting, thickening envelope. This residuum of heat would be but a small fraction of the potential energy of the molten globe. Regarded as a source of the heat energy represented in the igneous activity of the globe during the one or two billion years of geologic history, it seems wholly inadequate.

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[1] Jeffreys, Harold. The Earth, etc.; page 80, 1924. "The Thermal History of the Earth."

The Planetesimal origin of the earth implies the assembling of solid particles and gradual compression of the whole globe as it grew up from the core to its present diameter. The self-compression of the mass was very great, according to this view. Assuming that the mean density of the growing globe was that of the moon (specific gravity 3.34) the shrinkage to the actual density of the earth (specific gravity 5.53) was 725 miles on the radius.[1] Comparisons with Mars and Venus give smaller estimates, but also indicate very great shrinkage. The self-compression occurred during the growth of the globe, and the heat developed, whatever its total may have been, was to a large extent buried and retained. The condensation of the solid mass under the excessive pressures that ultimately developed was altogether internal and the heat was stored. The suggestion that the stored up energy may have been sufficient to cause melting from within outward lies close at hand.

Chamberlin, giving the results of his studies up to 1909 [1] and reasoning according to the then available evidence that the earth is solid to the center, disposed hypothetically of the excess of heat by conduction, melting, and extrusion of melted fractions. He assumed that conduction would be inadequate to carry off the excess, as is generally recognized, and that melting must occur; but he postulated that the melted masses would be pressed and kneaded out as fast as formed in sufficient quantity, so that the essentially solid state would be maintained.

Another source of heat beside compression is found in those atomic and molecular changes in which heat is given off, the so-called exothermic reactions. In a molten globe these would very largely be completed in the course of cooling and solidification. The resulting solid globe would have reached stability and the energy developed in the process would have been carried off by the magma and radiated away. In the globe which grew by gradual accretion the reactions would be delayed until they were facilitated or brought about by suitable increase of temperature, due to compression. The minerals would then be deeply buried and the heat would escape more or less slowly according to the depth of burial. Some of it would be used up in the opposite kind of reactions, the so-called endothermic changes in which heat energy is absorbed. Melting, for instance, is such a change and it produces a condition in consequence of which heat is lost to the globe by extrusion of the magmas. It is the process upon which Chamberlin relied to keep the earth solid in spite of the heating processes.

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[1] Chamberlin, T. C., The Self-compression of the Earth and Related Problems. Carnegie Institution of Washington, *Yearbook* 19, p. 367, 1920.

[1] Chamberlin, T. C., and Salisbury, R. D., "Manual of Geology," vol. I, pp. 564–567, 1909.

Radio-activity would supply stores of heat sufficient to melt the globe, or at least a large part of it, if the radio-active minerals were everywhere present in the proportion, slight though it is, in which they occur at the surface. Joly has pushed this inference to the conclusion that the outer shell of the earth to a depth of 25 miles (40 kilometers) has repeatedly been melted:[1] Jeffreys deals with the problem of the distribution of heat within the earth by checking estimates of the effect of radio-activity against observed temperature gradients, and concludes that radio-activity must diminish with depth and fall off to practically nothing in 8 to 10 miles (13 to 16 kilometers) below the surface.[2]

Reasons for the concentration of radio-active minerals in the outer crust of the earth are found in the fact that they promote melting and would therefore be found in the magmas that have risen to the surface. Holmes,[3] assuming a molten globe, regarded it as possible that the radioactive elements form volatile compounds which rise to the surface through the magma. His view is quoted favorably by Jeffreys. Chamberlin, reasoning regarding a solid globe in which, since an early stage of growth, melting has occurred locally, argued that the presence of radio-active elements would in itself constitute a local cause of melting, which would lead to the extrusion of magmas containing them. Thus the interior would be impoverished and the surface enriched.[1] The consensus of opinion appears to be that under any conditions of origin of the earth radioactivity is not an important source of heat in the deeper interior, and in all probability is effective only in the outermost shell.

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[1] Joly, John, "The Surface History of the Earth."

[2] Jeffreys, Harold, *Op. cit.*, page 84.

[3] Holmes, A., Radio-activity and the Earth's Thermal History, *Geological Magazine*, February, 1915, p. 64.

Any kind of mechanical stress which causes strain and thus does work is in some degree transformed into heat in the process. In the earth this heat is added to the general store. As a rule the stresses thus converted are very slight and the heat increment is inappreciable in comparison with the great stores available. It may happen, however, that repeated applications of transient stresses at the same place, in the presence of critical states of temperature and pressure, may produce an effect out of proportion to their real potency. Thus strain is a probable cause of melting, provided the rock be near the melting point under the actual conditions of pressure. By hypothesis tidal stresses may induce such strain, provided that their action is repeatedly concentrated at one and the same shearing plane. Or, in the case of a displacement on a fault plane, the work done in overcoming friction may cause recrystallization, metamorphism, and even melting.

Distribution of Heat.—It is well established by observation that temperature within the earth increases to the depth to which we can penetrate, and it is confidently inferred that it continues to rise at some significant rate to very great depths, if not to the center.

So far as can be observed in excavations, shafts, and boreholes, the change of temperature in the superficial rocks varies from 1 degree F. in 20 feet to 1 degree F. in 130 feet (1 degree C. in 10 meters to 1 degree C. in 70 meters). These are extremes. The general average is 1 degree F. in 50 to 60 feet (1 degree C. in 28 to 33 meters).[2]

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[1] Chamberlin, T. C., The Bearings of Radio-activity on Geology, *Jour. of Geology*, Vol. XIX, pp. 673–695, 1911.

[2] Chamberlin, T. C., and Salisbury, R. D., "Manual of Geology," vol. I, p. 569, 1909. For fuller information see reports of Committee on Underground Temperatures, British Association for Advancement of Science.

Were this rate of increase maintained to the center of the globe, the temperature would there exceed two hundred thousand degrees, an impossible figure. It is obvious that the rate of increase must fall off very rapidly below a thin, superficial layer, in order that the relations of temperature and pressure should be such as to give the earth the solidity it exhibits. Several temperature gradients have been calculated, according to different basic assumptions. The origin of the planet is involved, since the distribution of heat would not be the same in a globe cooled from a molten condition or assembled as a solid. The degree of solidity and the distribution of density enter into the estimates.

Assuming that the globe was once completely molten, that it solidified from the center outward, that the density increased with depth as the square root of the increase of pressure (Laplace law), and that the fusing point rose directly as the pressure, Chamberlin, on the basis of experiments by Barus, calculated a curve representing temperatures of fusion just below which the globe would be solid. The temperature at half radius would be 40,000 degrees C. and at the center 78,000 degrees C. These figures appear excessive. On the hypothesis that the globe grew up as a solid and that the heat developed gradually as the compression increased, Chamberlin, reached the conclusion that the temperature at half radius would be 16,000 degrees C. and at the center 32,000 degrees C. The temperature gradient is not represented by a straight line, as might be inferred, but by a curve that passes through an inflexion about one-fourth of the radius below the surface. The effect in the change of direction of curvature is to indicate that heat does not escape so rapidly through the outer shell, in general, as it rises through the deeper portion. This suggestion bears significantly upon the problems of local melting in the otherwise solid globe.

In the Manual referred to (pages 559–574) Chamberlin presents alternative estimates of the distribution of heat, and discusses them. The student is referred to his treatment of the subject for further information regarding the assumptions and their bearing on geologic problems. It should be borne in mind, however, that certain advances in our knowledge of the globe have been made since 1909. The seismologic evidence indicates that a marked change in the state of matter occurs at about half the radius, at the surface of the core. The indication is that the core is non-solid, presumably because it is so hot. The hypothetical curve would therefore end at the surface of the core. The temperature would presumably be higher in proximity to the core, and the rate of decline would be sharper.

Jeffreys has considered the rate of cooling at great depths, taking account of the presence of radio-active substances, and he distinguishes between subcontinental and suboceanic regions. For subcontinental depths he assumes an initial temperature of 1,200 degrees C. at the surface and about 1,450 degrees at a depth of 500 miles (800 kilometers). The globe having now cooled practically to 00 degree at the surface, he finds that the temperature 500 miles below the surface would remain unchanged. For suboceanic masses he estimates that the cooling would have been substantially greater, provided certain assumptions regarding the distribution of radio-active substances and the method of formation of the continents hold true. The chief value of these estimates appears to lie in the demonstration that cooling by conduction through rocks is excessively slow.[1]

L. H. Adams has also made calculations of the actual distribution of temperature in the globe, on the assumption that it was initially molten and cooled by radiation and convection. His results are given in Fig. 151. The initial temperature is that which the earth is supposed to have had after convective cooling had ceased to play its role; that is, when complete solidification was approached. Cooling thenceforward was by conduction.[2]

In considering these estimates of the distribution of temperature, the student should note the assumptions which are implied as well as those that are explicitly stated. Among the latter is the stated distinction between the molten and planetesimal origin of the globe, which is fundamental. Equally important, but not stated, is the assumption that the earth is layered like an onion. It is implied that the changes in constitution, pressure, and temperature are the same along any one radius as along any other. The facts of the surface distribution of rocks, the form of the earth, and the irregularities of its rotation, all indicate that masses of different composition and density are somewhat irregularly distributed in the globe. Even on the assumption of the persistence of a molten state during geologic ages, it would be contrary to experience to suppose that so large a mass could have become arranged in homogeneous layers. The differences of density of magmas would not suffice to cause complete rearrangement of the highly vis-

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[1] JEFFREYS, HAROLD, *Op. cit.*, p. 89, 1924.

[2] ADAMS, L. H., Temperatures at Moderate Depths within the Earth. *Journal* Washington Academy of Sciences, vol. XIV, pp. 459–472, 1924.

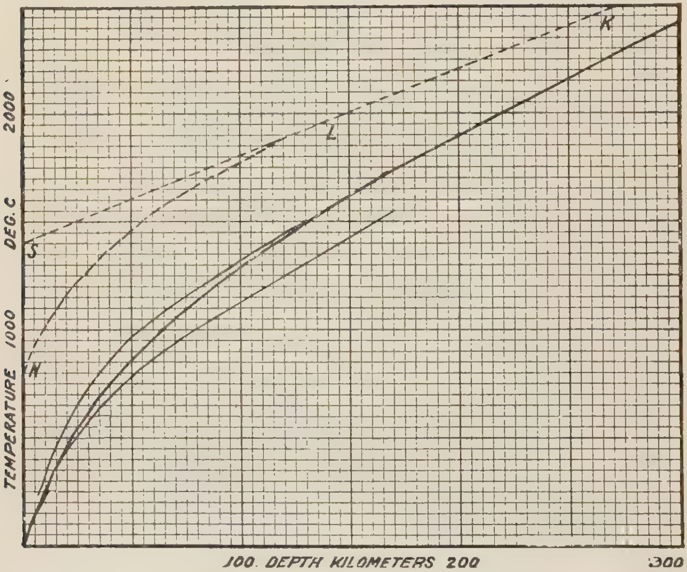

Fig. 151.—The heavy line indicates the most probable temperatures at various depths down to 300 km. (180 miles). The "initial" temperature is shown by the line *NLK*, but the line *SLK* leads to substantially the same result, because the present temperatures of the Earth are independent of the original temperatures in the upper 100 km.

cous melts. The ingathering of planetesimals to form a solid globe would not provide any method of screening denser from lighter or of uniform spreading of the infalls over the surface. Atmospheric circulation, in so far as it might affect the result, would tend to cause denser to assemble with denser and lighter with lighter, as pointed out by Chamberlin.[1]

Whatever the original organization of material in approximately homogeneous layers may have been, the subsequent eruptive activity of the earth's interior must have caused dikes of all kinds to penetrate from level to level and to introduce materials of unlike composition and density into all parts of it. There is reason to believe that these masses are of notable size, even in comparison with continental masses. Thus it appears that speculation regarding a homogeneous earth or based upon that concept can represent little more than an academic theory. They afford valuable suggestions and place useful limitations upon geologic research, but they may not be accepted as representing the facts.

If we apply this reservation to the estimates that have been given, we must recognize that under any group of assumptions the internal heat distribution is more variable than the smoothly drawn heat gradients suggest. Or, considering hypothetical surfaces of uniform temperature, the iso-geothermal surfaces of the globe, we would not conceive them to be smooth spheroids, but warped surfaces which may be greatly depressed or notably raised with reference to their average position.

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[1] Chamberlin, T. C., "The Origin of the Earth, Formative Stages," pp. 197–200, 1916.

CHAPTER XIX

DYNAMIC SPHERES OF THE GLOBE

Use of the phrase dynamic sphere. The forces of the globe not in a state of balance, but of balancing with each other. The core of the earth; distinctness of its surface; its dynamic condition; its state; its potency. The envelope; conduction of heat through it; Lunn's conclusions; its heterogeneity; three divisions of the envelope. The stereosphere or sphere of strength; the asthenosphere or sphere of weakness; the outer crust.

DEFINITION

Let us define a dynamic sphere as a large part of the globe which is characterized by a peculiar balancing of forces.

The word sphere is used in this sense as it is in the familiar term atmosphere, and may indicate an envelope or shell of the earth or, as in the case of the hydrosphere, a shell that is not entirely complete. As a matter of course, sphere also applies appropriately to any central spherical mass or core.

The phrase balancing of forces is used to designate the dynamic condition that is supposed to distinguish one sphere from another. For instance, the atmosphere is characterized by the general equilibrium between the dispersive activities of the gases and the gravitational attraction of the earth. It serves to illustrate the use of the word balancing. The state of balance may be complete in a perfectly still body of air, but in general that condition is one toward which the substance of the sphere strives, as is the case where winds and currents exist. The stability of the earth demonstrates that there is a tendency to balance among the internal forces, but gradual movements of the surface and occasionally violent local disturbances indicate a state of balancing toward a more complete equilibrium of stresses.

THE CORE

The very probable existence of a metallic core has already been stated, and it has been described as a sphere some 2,200 miles (3,470 kilometers) in radius. This is one-half of the radius of the earth and the volume of the core is therefore one-eighth of the total, but its mass is relatively large because of the very high density, which is estimated to be about ten times that of water.

The existence of the core is inferred from calculations based upon the average density of the earth, but is more conclusively demonstrated by the interception of earthquake vibrations. We have already quoted from Macelwane the statement that the surface of the core is so well defined that it can be located within an error of 20 miles (30 kilometers). This remarkably precise estimate is based upon calculations of the points on the surface of the core at which earthquake waves enter and leave it. At the request of Bailey Willis, Father William C. Repetti, S. J., calculated some twenty points of entrance and exit of waves passing from a known earthquake focus to a seismological station at which it was recorded, and determined the geographical coordinates (latitude and longitude) of the points on the core. Upon plotting these positions on a globe it was found that they fell indifferently in oceanic and continental areas. All of the calculations indicated approximately the same radius for the core. It thus appeared that there was no correspondence which could be detected between any possible irregularities on the surface of the core and those which constitute the ocean basins and the continents of the outer surface. This is presumably what we should expect.

The dynamic condition of the core may probably be best described as that of a superheated body. Under any hypothesis of the origin of the earth it must be presumed to be exceedingly hot. The fact that transverse earthquake vibrations do not pass through it may be attributed to an inelastic, non-solid state due to excessive heat, or, alternatively, to extreme density. In view of the undoubtedly high temperature, the latter possibility seems improbable and the weight of evidence is in favor of the molten condition. Among the items which support that inference is the rather precise definition of the boundary between the core and the surrounding envelope. The envelope is certainly solid. If the core were also solid it would be difficult to account for the development of the sharp boundary; whereas, if the core be molten the passage from one to the other might readily occur in a few kilometers.

On the assumption that the core is a superheated, non-solid body, presumably molten, we must recognize in it a dynamic sphere of very great potency, one in which there are enormous stores of energy.

DIVISIONS OF THE ENVELOPE

Completely surrounding the core and extending from it to the surface of the earth is an envelope of igneous rock having a total thickness of 1,800 miles (2,900 kilometers). Upon the evidence of seismic waves Macelwane has divided this thickness into several shells, as quoted in Chapter XVI, page 412. The shells thus distinguished differ in those conditions which affect the speed of earthquake waves, namely elasticity and density; and these depend on composition, pressure, and temperature. The available evidence does not permit us to disentangle the three last-named conditions. Petrologists hold that the composition of the great mass of igneous rock is basic, that the envelope consists of basalt, peridotite, or ultra-basic silicates, possibly of compositions unknown at the surface. The physico-chemical studies are sustained by the speed of transmission of the earthquake waves, which has been experimentally shown to require the elasticity of peridotite or heavier rock species. Accepting these conclusions as true in a large way, we have to recognize that in detail the constitution of the envelope may depart materially from the hypothetical average. A large number of earthquake waves fail to be recorded; they are lost by absorption, reflection, or refraction. In many cases the elastic transverse wave is lost, and we might then infer that it had met a molten mass a few kilometers thick which had absorbed it. In other cases, however, it is the longitudinal wave which is lost, and then reflection or refraction is indicated as the cause. Sometimes both waves are lost and there is no record whatever of a wave which should have come through on a certain path. These negative observations leave us in doubt as to the specific cause of their occurrence, but they clearly indicate that the envelope is heterogeneous, and whatever its average composition at any depth, it is composed of bodies that differ from one another in their physical characteristics, and that are in contact on surfaces sufficiently well defined to divert elastic waves. The envelope is not homogeneous or isotropic.

In order to consider the thermal condition of the envelope we turn to the studies of A. C. Lunn [1] under the guidance of Chamberlin. Lunn deduced a curve of internal temperature upon assumptions of compression, conduction, and radiation stated in his paper, and reached the conclusion that the flow of heat from the center outward to six- or seven-tenths of the radius would be faster than the flow from eight-tenths of the radius to the surface, neglecting the immediate surface effects of external cooling. This conclusion is the basis of a distinction between the inner part of the envelope and an outer shell.

We divide the total thickness of the envelope of igneous rocks into three shells. Starting from the surface of the core, we take 1,000 miles (1,600 kilometers) as that portion of the envelope in which the flow of heat is faster than it is above that. This leaves 800 miles (1,280 kilometers) in which the flow is slower. From this latter figure we take 30 miles (48 kilometers) as representing the outer crust of the earth which corresponds to the zone of fracture.

The shell corresponding to the innermost thousand miles we will call the *stereosphere*, a new term introduced to express the inference that it is a relatively strong, rigid shell.

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[1] Lunn, A. C., Geophysical Theory under the Planetesimal Hypothesis; *In* Contributions to Cosmogony and the Fundamental Problems of Geology. Carnegie Institution of Washington, *Publication* No. 107, 1909.

Chamberlain, T. C. and Salisbury, R. D., "Manual of Geology," p. 566, 1909.

Surrounding the stereosphere lies a shell through which, according to the calculations of Lunn, heat flows more slowly than it does in the inner shell. The temperature should therefore rise in the outer shell and from time to time should reach an intensity at which local melting would result. The shell is therefore relatively weak and for that reason was named by Barrell [1] the *asthenosphere*, or shell of weakness. Subtracting the outer crust or zone of fracture from the total thickness, we have for the asthenosphere the remainder of 770 miles (1,240 kilometers).

Thus we recognize as divisions of the envelope the stereosphere or sphere of strength, the asthenosphere or sphere of weakness, and the crust or zone of fracture.

THE STEREOSPHERE

The stereosphere surrounds the superheated core. It therefore receives heat energy at its inner surface and conducts the heat outward at a rate determined by the composition and density of the rock. That rate is thought to be such that the flow of heat is nowhere impeded, and the temperature falls off as the energy is diffused in the larger volume corresponding to the increasing radius. According to Lunn the temperature at the inner surface of the stereosphere would be about 12,000 degrees C. This figure was reached, however, on the assumption that starting with 20,000 degrees C. at the center, the temperature fell off to 12,000 at half the radius. If for the solid core we substitute the conception of a molten state, the temperature at the inner surface of the stereosphere would presumably materially exceed Lunn's estimate, and this would modify the rest of his curve. The figures suffice, however, to indicate approximately the intensity of internal heat, which would certainly not fall below these estimates.

Pressure in the stereosphere is also very high. At the greatest depth, at the surface of the core, it is estimated to be 1,600,000 atmospheres or 23 million pounds per square inch (1,600,000 kilograms per square centimeter). At the outer surface of the stereosphere, 1,000 miles above its inner surface, the pressure would be about 260,000 atmospheres or 3,800,000 pounds to the square inch (260,000 kilograms per square centimeter).

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[1] BARRELL, JOSEPH, The Strength of the Earth's Crust, the Asthenosphere. *Journal of Geology*, vol. XXII, pp. 680–683, 1914.

The solid elastic state of the stereosphere is attributable to the controlling influence of pressure, which prevents the rock from melting in spite of the high temperature. We may deduce a hint of the relations between heat and pressure from the seismologic data on the velocity of earthquake waves. That velocity increases from above downward in the upper part of the stereosphere and decreases in the lower part (see Chapter XVI, p. 412). The increase in speed can only be attributed to increased elasticity, while the decrease may be due to higher density or relatively more influential high temperature. It is logical to infer, therefore, that temperature is more nearly able to overcome pressure and produce melting in the lower part of the stereosphere than in the upper part.

THE ASTHENOSPHERE

The asthenosphere is that shell of the earth, 770 miles (1,240 kilometers) thick, which surrounds the stereosphere and extends up to the bottom of the outer crust. Its dynamic characteristic is that heat accumulates in it until relieved by melting and extrusion. As has been stated, this postulate was originally due to Chamberlin and was developed by Barrell. The principal reason assignable for the accumulation of heat is that the density is lower and conductivity therefore slower than in the stereosphere. It appears from general considerations regarding conductivity that this assumption must be correct, but it has not been proved experimentally. In fact, Bridgman's experiments on the conductivity of metals under pressure indicate that some though not all alloys lose in conductivity as pressure is increased.[1]

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[1] Bridgman, W. P., *Proceedings*, American Academy of Sciences, vol. 57, p. 75, 1922.

A comparison with alloys does not, however, apply directly to crystalline rocks, there being differences of molecular structure between rocks and metals sufficient to invalidate any comparison. Studies of the conductivity of crystals show that there are differences according to the direction of flow of heat, whether perpendicular or parallel to a major axis. There are also material differences in the conductivity of different kinds of rocks, acid rocks being better conductors than the more basic. Any attempt to assign relative values to these different factors and to draw a general conclusion regarding the greater or less conductivity of the asthenosphere would be open to question. Lunn's inference, therefore, is not confirmed; neither can it be denied. On the other hand, it is obvious that the variable factors which affect conductivity will condition different masses of rocks in different degrees. Let it be assumed that a mass of higher conductivity may come to lie beneath one of lower conductivity, or vice versa, in a heterogeneous shell. The flow of heat would be impeded or facilitated accordingly, and the distribution of temperature effects would be irregular at higher levels. This is what we observe on the surface, and the correspondence strengthens the inference that heat flows irregularly through the asthenosphere.

The normal or mean temperature in the asthenosphere would be lower than in the stereosphere, and the upper portion of the asthenosphere would be cooler than the lower. But these normal conditions would be distributed by irregularities of conductivity, and the distribution of temperature would therefore be variable vertically and horizontally.

Pressures in the asthenosphere diminish from 260,000 atmospheres at the bottom to about 17,000 atmospheres or 250,000 pounds per square inch (17,000 kilograms per square centimeter) at the top. The testimony of earthquake waves is that in general the asthenosphere is elastic and solid, and pressure within it is therefore normally preponderant over temperature. But since pressure due to gravity is relatively invariable, and conditions for local rises of temperature are postulated, it follows that melting would occur locally.

Local melting, with the production of magma, would have but little effect upon the distribution of temperature or the stability of the overlying crust, even if the bodies of magma were large, unless the magma were extruded.

THE OUTER CRUST

We have briefly described the core, the stereosphere, and the asthenosphere. They constitute the three great dynamic spheres of the globe, for in them are stored the potentialities of its activity. The outermost shell, the outer crust or skin, is very thin and comparatively impotent; but it plays an important part in producing the features at the surface, because it acts as a very rigid layer to transmit thrusts, and the rocks of which it is composed are capable of metamorphic changes which develop intense pressures. The mechanical conditions that characterize it have already been described in Chapter XVIII. It is subject to disturbance from within in consequence of the rise of magmas from below and the mechanical and metamorphic effects which they produce.

APPENDICES

APPENDIX I

Correction for Dip in Direction Not Perpendicular to Strike [1]

Angle of Full Dip	Angle Between Strike and Direction of Section							
	80°	75°	70°	65°	60°	55°	50°	45°
10°	10°	10°	9°	9°	9°	8°	8°	7°
15°	15°	14°	14°	14°	13°	12°	12°	10°
20°	20°	19°	19°	18°	18°	17°	16°	14°
25°	25°	24°	24°	23°	22°	21°	20°	18°
30°	30°	29°	28°	28°	27°	25°	24°	22°
35°	35°	34°	33°	32°	31°	30°	28°	26°
40°	40°	39°	38°	37°	36°	35°	33°	31°
45°	45°	44°	43°	42°	41°	39°	37°	35°
50°	50°	49°	48°	47°	46°	44°	42°	40°
55°	55°	54°	53°	52°	51°	49°	48°	45°
60°	60°	59°	58°	58°	56°	55°	53°	51°
65°	65°	64°	64°	63°	62°	60°	59°	57°
70°	70°	69°	69°	69°	68°	67°	65°	63°
75°	75°	74°	74°	74°	73°	72°	71°	69°
80°	80°	80°	79°	79°	78°	78°	77°	76°
85°	85°	85°	85°	84°	84°	84°	83°	83°

[1] Modified after Lahee.

Correction for Dip in Direction Not Perpendicular to Strike (Cont'd)

Angle of Full Dip	Angle Between Strike and Direction of Section							
	40°	35°	30°	25°	20°	15°	10°	5°
10°	6°	6°	5°	4°	3°	3°	2°	1°
15°	10°	9°	8°	6°	5°	4°	3°	1°
20°	13°	12°	10°	9°	7°	5°	4°	2°
25°	17°	15°	13°	11°	9°	7°	5°	2°
30°	20°	18°	16°	14°	11°	9°	6°	3°
35°	24°	22°	19°	16°	13°	10°	7°	4°
40°	28°	26°	23°	20°	16°	12°	8°	4°
45°	33°	30°	27°	23°	19°	15°	10°	5°
50°	37°	34°	31°	27°	22°	17°	12°	6°
55°	43°	39°	36°	31°	26°	20°	14°	7°
60°	48°	45°	41°	36°	30°	24°	17°	9°
65°	54°	51°	4 °	42°	36°	29°	20°	11°
70°	60°	58°	54°	49°	43°	35°	25°	13°
75°	67°	65°	62°	58°	52°	44°	33°	18°
80°	75°	73°	71°	67°	63°	56°	45°	26°
85°	82°	81°	80°	78°	76°	71°	63°	45°

APPENDIX II

Proposition.—The plane of maximum unit shearing stress makes an angle of 45 degrees with the direction of the initial pressure, provided the material sheared is ideally rigid.

Discussion.—Assume a force P acting upon a mass of which $ABCD$ is any cross-section, and take P perpendicular to the surface represented by AB. The pressure P will set up in $ABCD$ a system of stresses radiating in every direction in the mass from the point of application. It is required to find the maximum unit shearing stress, that is, the shearing stress which has the greatest intensity per unit of area of the surface of the shear. (Fig. 152.)

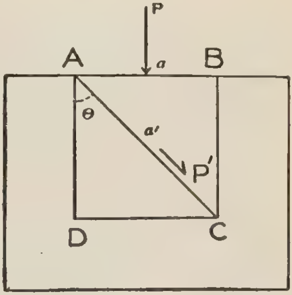


FIG. 152—Diagram illustrating the law of maximum shear.

Let P equal the initial pressure on a unit of area a. Assume any shearing stress making an angle θ with the direction of P. Let P' represent the shearing stress at that angle. It is distributed over the area a' and the intensity of the unit shearing stress will be P'/a'.

Now $a' : 1$ as $a : \sin\theta$ and a' equals $a/\sin\theta$.

Also P' equals $P\cos\theta$.

Designate the unit stress by S. Then S equals P'/a', equals $P\cos\theta\sin\theta/a$.

But by trigonometry, $\cos\theta\sin\theta$ equals $\frac{1}{2}\sin 2\theta$, and a equals 1. Hence: S equals $\frac{1}{2}P\sin 2\theta$. The variable in this equation is the angle θ, which may range from zero to 90 degrees. At either extreme the $\sin 2\theta$ is zero and the shearing stress is zero. But $\sin 2\theta$ is a maximum when 2θ equals 90 degrees or θ equals 45 degrees.

Hence it follows that the unit shearing stress S will have its maximum value in a plane inclined at an angle of 45 degrees to the initial pressure.

APPENDIX III

(The following plates are taken from "Mechanics of Appalachian Structure," by Bailey Willis, 1893.)

PLATE A

Many preceding experiments indicated that initial or consequent dips in the models determined the positions of anticlines. Therfore the SB models were constructed to test the control exercised by dip.

Description of Model 1

Original length, 39$\frac{3}{8}$ inches = 1 meter. Fig. *a*.
Width, 5 inches.
Thickness, 3$\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1	1	1	0	$\frac{1}{2}$	Hard
2 to 13 (inclusive)	1	1	0	$12\times\frac{1}{8}$	"
14	1	0	$\frac{1}{2}$	2$\frac{1}{2}$	Soft

The soft base was cut to the form shown in Fig. *a*, and the hard layers were placed upon it under a load of 1,100 pounds and allowed to stand two hours. They then conformed to the initial dips required by the base, Fig. *a*, with the marked change in dip 6 inches from the applied force.

Under uniformly distributed load of 1,100 pounds, equal to about 5$\frac{1}{2}$ pounds per square inch of original length, the model was compressed three times, as shown in Figs. *b* to *d*.

Results

An anticline was formed with the acute crest of the arch coincident with the upper line of initial dip. The anticline was competent, as shown by the tunnel within it, and continued compression closed it, forming a carinate fold, Figs. *b*, *c*, and *d*.

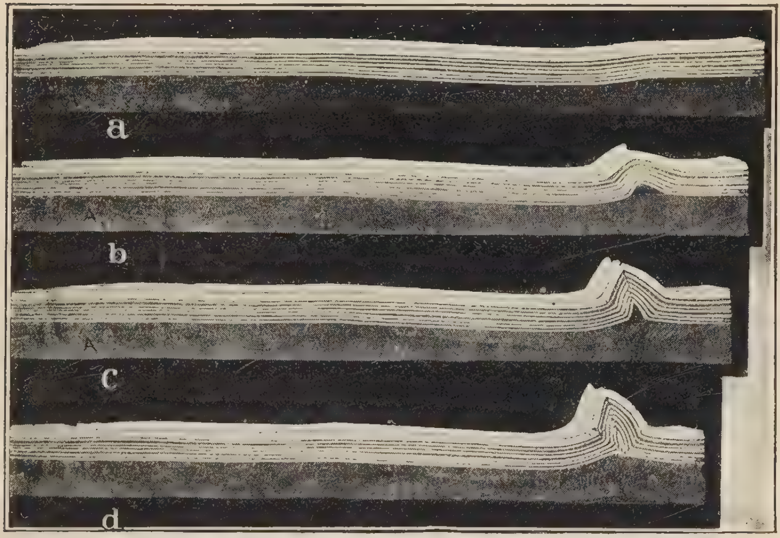
DESCRIPTION OF MODEL 2, FIGS. *a′* AND *b′*

This model was constructed of the same materials and after the same manner as the preceding, but with the line of the initial dip at 18 inches, or three times the distance from the applied force.

It was compressed once, under load like the preceding.

Results

An anticline, similar in form to that obtained in Model 1, rose at the line of assumed dip.



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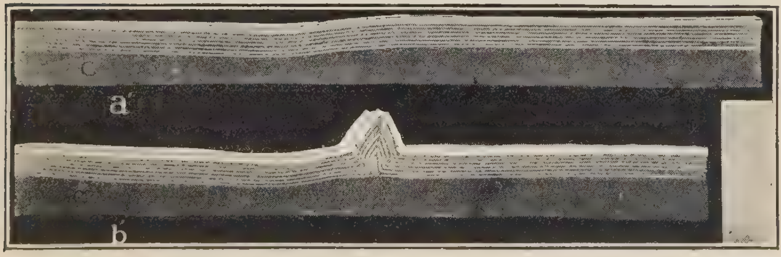


2

PLATE A

PLATE B

DESCRIPTION OF MODEL

Original length, 30 inches. Fig. *a*.
Width, 6 inches.
Thickness, 5 inches.

Layers	Composition (Parts by Weight)			Thickness	Characters
	Wax	Plaster	V. Turpentine	Inches	
1	1	2	0	$\frac{1}{8}$	Very hard
2	1	0	$\frac{1}{2}$	1	Soft
3 to 14 (inclusive	1	1	0	$12\times\frac{5}{32}$	Hard
15	1	1	0	1	"
16	..	0	$\frac{1}{2}$	1	Soft

The model was designed to show the nature of a fold in a series composed of a thick hard bed (15) underlying a number of thin beds. Under a uniformly distributed load of 500 pounds, equal to 2¾ pounds per square inch on the original length, it was compressed, as shown in Fig. *b*

Results

Figure *b*. The thick, hard stratum (15) formed an anticline 10 inches from the applied force and broke on the axis. The overlying thin, hard strata were carried up on this anticline and assumed a flat position between it and the load, with steep dips on either limb. The weight borne by the steeper limb of the anticline squeezed the soft layer (16), and this effect, combined with a scarcely noticeable initial dip in Fig. *a*, caused a second anticline to commence at 7½ inches from the resistance. The soft layers flowed into these arches.

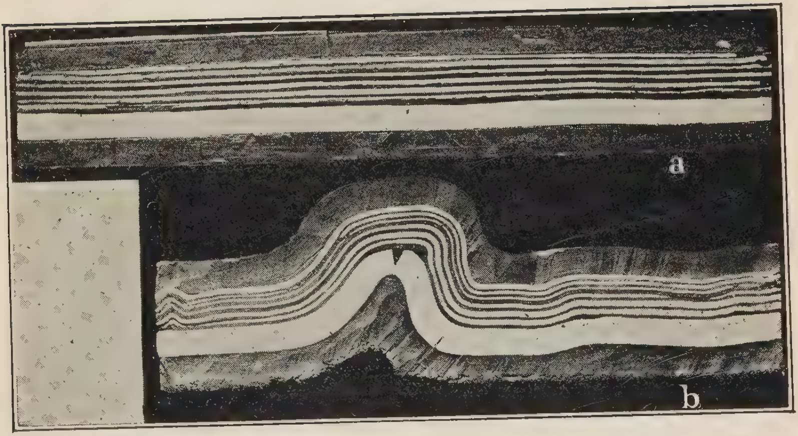


PLATE B

PLATE C

Description of Model

Original length, 26½ inches (not shown).
Width, 6 inches.
Thickness, 2⅞ inches.

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1	1	1	0	⅜	Hard
2 to 13 (inclusive)	1	1	0	12×⅛	"
14	1	0	½	1	Soft

The model was designed to show the nature of a fold in a series composed of a thick hard bed over many thin hard beds; the difference of thickness assumed was moderate.

Under a uniformly distributed load of 500 pounds, equal to about 3.15 pounds per square inch on the original length, it was compressed four times.

Results

Figure *a*. The hard strata (1 to 13 inclusive) forming a thick but weak series, did not rise in a clearly competent anticline with this degree of shortening; but the soft layer (14) swelled and gave them an initial arch of flat crown, which exceeded the competent dip-length.

Figure *b*. The pressure transmitted upward through the nearer limb of the initial arch raised it and formed a flat but competent anticline. The weight borne by the further limb of the anticline squeezed the soft layer (14) and gave rise to subsequent dips and the beginning of the consequent anticline. There is slight curvature of the strata near the resistance.

Figure *c*. The first anticline is nearly closed in carinate form; the second has developed with a sharp crest and a small keel in the lowest hard layer (13), showing that it was competent, but was nearly filled by the flow of soft material from the region of increased weight to that of relief from load. The soft base has thickened near the resistance and has produced initial dips in the hard strata, which arch over a small tunnel, showing the beginning of a competent anticline.

Figure *d*. The folds previously determined are developed to closing without other deformation. The steeper dips throughout the whole series are toward the lower synclines and are directed both toward and away from the applied force.

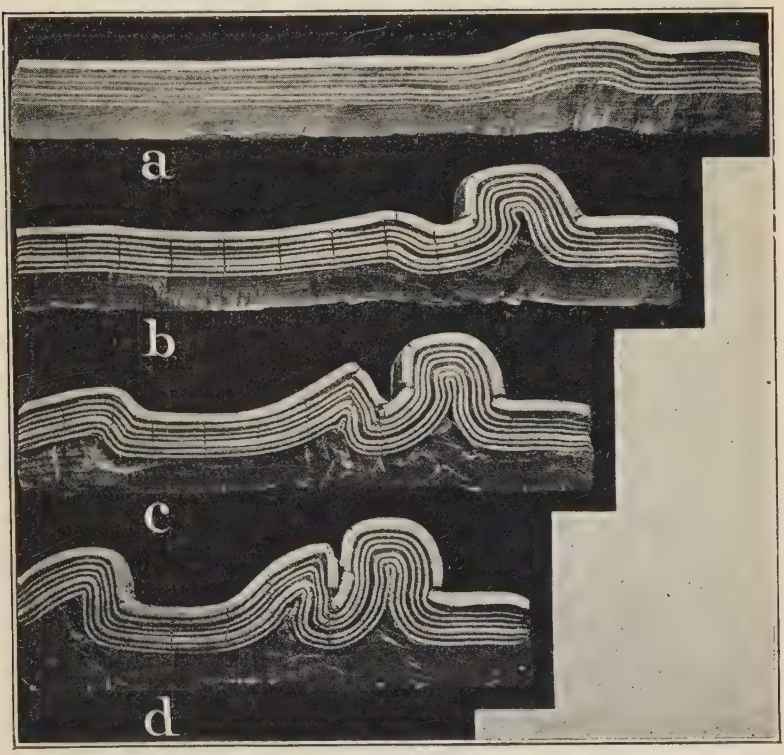


Plate C

PLATE D

DESCRIPTION OF MODEL

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.
Width, 5 inches.
Thickness, $2\frac{1}{2}$ to $3\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1 to 12 (inclusive)	1	1	$\frac{4}{9}$	$12\times\frac{1}{16}$	Soft
13	1	1	$\frac{4}{9}$	$\frac{1}{2}$	"
14 to 17 (inclusive)	1	1	$\frac{4}{9}$	$4\times\frac{1}{16}$	"
18	1	0	$1\frac{1}{2}$	1 to 2	Very soft

Under uniform load of 1,100 pounds this model was compressed six times, in order to test the nature of the consequent development of strata, which it was supposed would be more likely to predominate upon the softer base.

Results

In Fig. *b* there is a thickening of the base and the initial development of two consequent folds. These folds continued to develop with minor contortion, and the second from the applied force became an important carinate anticline with a detached anticlinal core, involving minor folds upon its limbs. The initial dip remote from the force was slowly accented from stage to stage of compression, but did not at any time develop a fold.

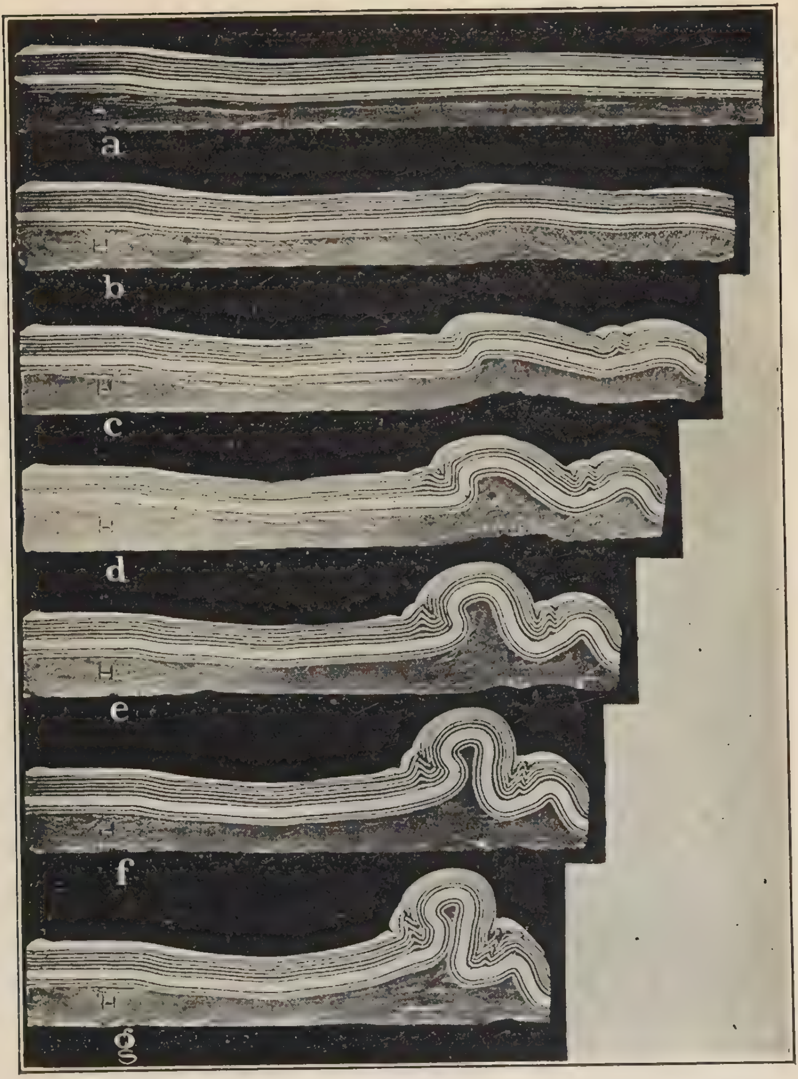


PLATE D

PLATE E

Description of Model

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.
Width, 5 inches.
Thickness, $1\frac{3}{4}$ to $3\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1 and 2	1	1	$\frac{4}{9}$	$2\times\frac{1}{16}$	Soft
3	1	1	$\frac{4}{9}$	$\frac{3}{4}$	"
4 to 7	1	1	$\frac{4}{9}$	$4\times\frac{1}{16}$	"
8	1	0	$1\frac{1}{2}$	0 to $1\frac{3}{4}$	Very soft
9	1	1	$\frac{4}{9}$	$\frac{1}{16}$	Soft

This model was designed with the intention of removing the influence due to pressure against the soft base and consequent swelling in advance of the piston. The bottom layer was introduced because the thick layer which would otherwise form the base was so soft that the model could not be handled.

Under a uniform load of 1,100 pounds the model was compressed six times, as shown in Figs. *b* to *g*. In Fig. *b* the initial synclinal form is exaggerated, and in Fig. *c* the tendency to depression in the syncline nearest the applied force, which was resisted by the firm base of the box, was deflected upward, causing an anticline upon the slope toward the force. This anticline in turn caused a second fold in advance of it, which became the predominant feature of deformation.

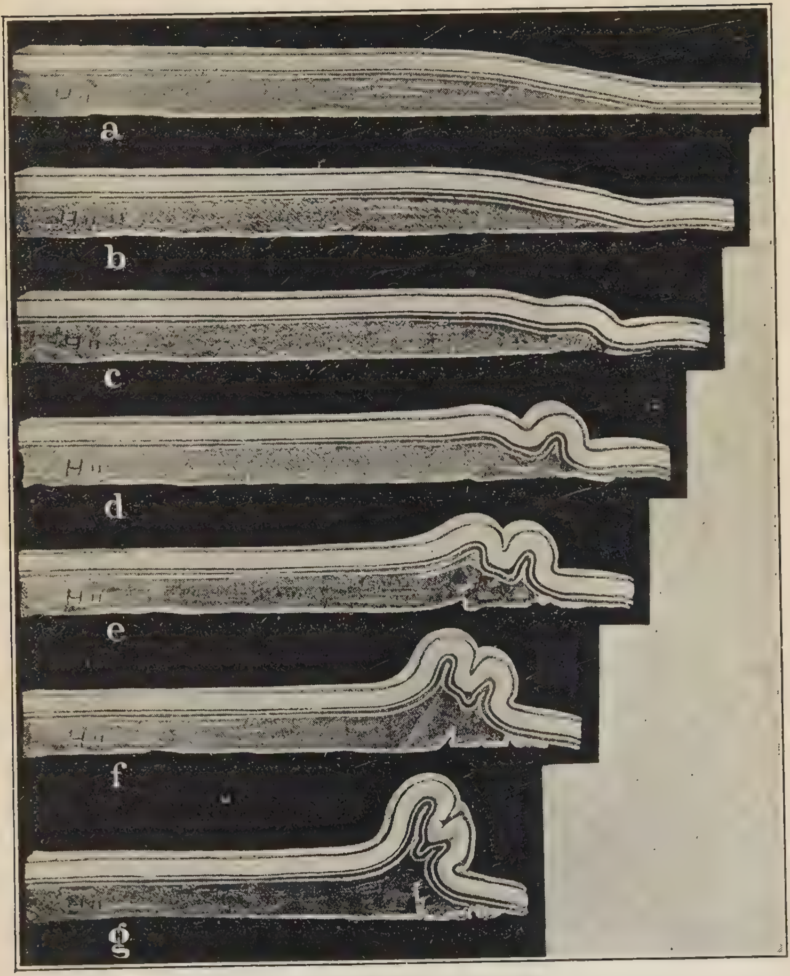


Plate E

PLATE F

In this model, the strata above the plastic base had the form of a very gentle initial syncline, as shown in Fig. *a*. It was supposed that such a syncline might develop in actual strata in consequence of the deposition of unequal thicknesses, and that the occurrence of greater thickness over the synclinal area might be influential in affecting the character of the folds. In order to test this idea several models were constructed, and pressure was applied to the synclines from different ends.

Description of Model

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, $3\frac{1}{2}$ to $4\frac{1}{2}$ inches, with syncline of deposition arranged with its axis at 27 inches from the applied force.

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1 to 8	*1	*1	*$\frac{2}{9}$	1 to 2	Soft but firm
9	1	1	$\frac{2}{9}$	$\frac{1}{2}$	“ “
10 to 15 (inclusive)	1	1	$\frac{2}{9}$	$\frac{1}{2}$	“ “
16	1	0	3	1 to $2\frac{1}{2}$	Very soft

* Including the thickness of the syncline.

Under a uniform load of 1,100 pounds this model was compressed six times, as shown in Figs. *b* to *g*.

Results

The original syncline was preserved throughout until the pressure of the piston below the crest of the consequent anticlines pushed in a wedge of folded strata which exaggerated the dip from the applied force. The thickening of the very soft base, in this as in other similar cases, produced two consequent folds near the applied force, the further one of which became the more important and developed into a carinate anticline.

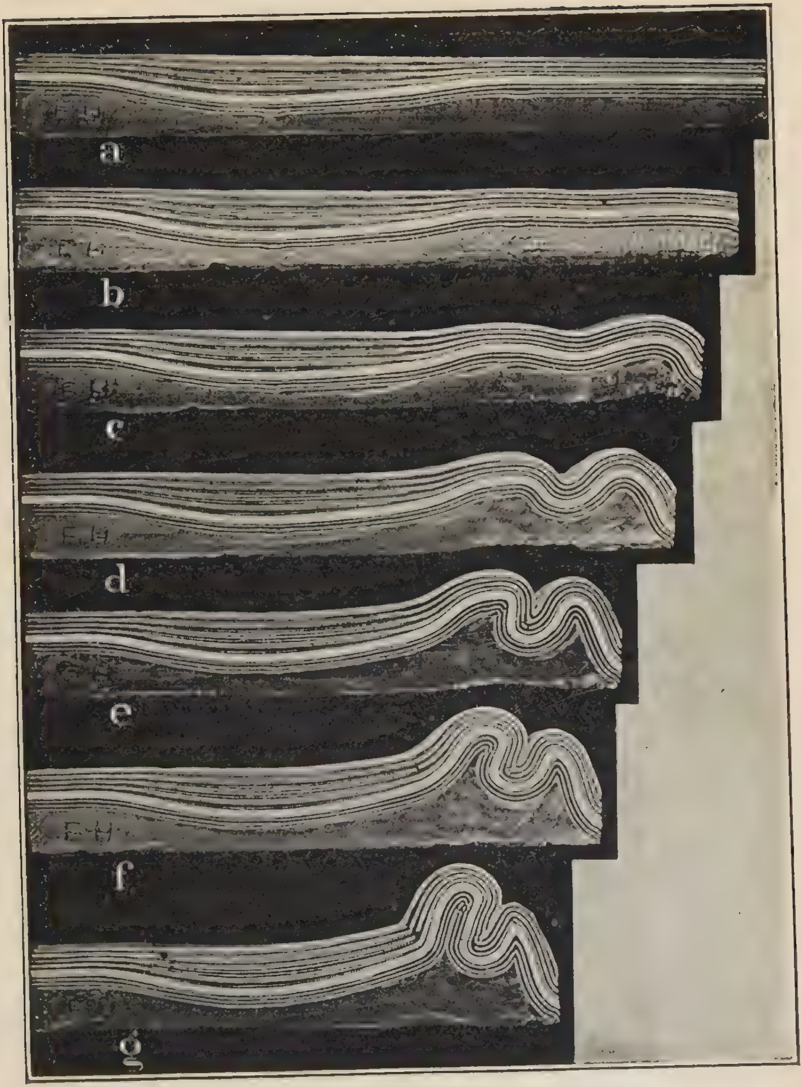


PLATE F

PLATE G

Description of Model V
Original length, 39⅜ inches = 1 meter. **Fig.** *a.*
Width, 5 inches.
Thickness, 3½ inches.
Preliminary pile, full thickness shown at left end.

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1 white 3 black 4 white 5 black 6 white	1	1	1	¾	Soft, but firm
7 to 12 (13 black)	1	1	2	¾	Very soft
14 white 15 to 19 20 white	1	1	3	1¼	Soft as butter at 70° F.

This pile having been made it was cut away on the bottom by a very small amount each time, as many times as there are layers at the right end above the thick white one (1); the cutting was unequal, and gave the bottom at each shaving an uneven surface. After each shaving the model was turned upon its bottom and pressed down on a flat surface, producing in the top a gentle syncline in which a thin layer could be cast. When this was cooled, the bottom was shaved again, the model was again pressed on a flat surface and a second thin layer cast in the new depression. Thus after many shavings and castings the thick white layer (1) was depressed at the right-hand end like a stratum sunk beneath a mass of comformable deposits of unequal thickness, and it extended diagonally through the model with variable initial dips. At the right-hand end the casting consisted of:

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1 to 19 20 heavier black	1	1	1	1¾	Soft, but firm
21 to 42	1	1	3	1¼	Soft as butter at 70° F.
1 of left-end white	1	1	1	½	Soft, but firm

Under a uniform load of 1,100 pounds the model was compressed nine times, three stages being shown in *c*, *e*, and *g*.

Results

(This represents pressure applied to thick strata in a syncline of deposition.) The initial dips in the principal diagonal layer, extending from the base at the right to the top at the left, controlled the important features of deformation. In Fig. *c* a single competent anticline rose at the nearer initial curve. A small consequent anticline, begun in Fig. *g*, lies beyond this one. The nature of minor deformation was determined by the plasticity of the materials. The soft but firm layers (1 to 20) folded in little anticlines and synclines. The butter-like material folded and also sheared on small fault-planes. The softest material was squeezed from the limbs into the axial regions of the folds.

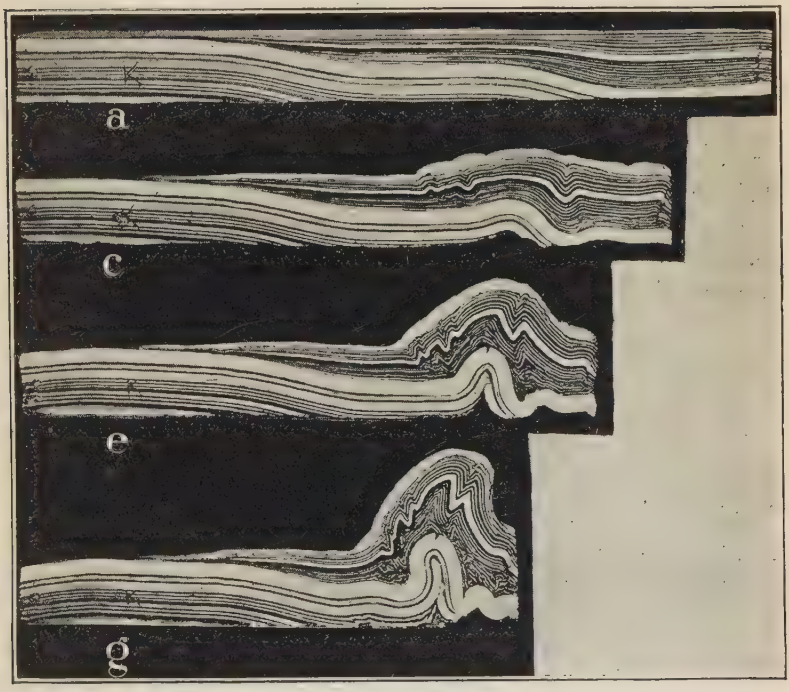


Plate G

PLATE H

Description of Model

Original length, $39\frac{3}{8}$ inches = 1 meter. Fig. *a*.
Width, 5 inches.
Thickness, $5\frac{1}{2}$ inches.
Preliminary pile, full thickness shown at both ends.

Layers	Composition (Parts by Weight)			Thickness Inches	Character
	Wax	Plaster	V. Turpentine		
1 black	1	1	$\frac{4}{9}$	1	Relatively hard but flexible
2 white 3 black 4 white 5 gray	1	1	3	$\frac{1}{4}$ 1 $\frac{1}{4}$ $1\frac{1}{2}$	Soft as butter at 70° F.

This pile was shaved unevenly on the bottom, pressed down flat, and filled in until a syncline was formed, Fig. *a*. Then additional layers were cast conformably over the whole length. The material with which the syncline was filled was of the softest character (wax, 1; plaster, 1; V. turpentine, 3). The overlying layers were of varied but firmer composition.

Layers	Composition (Parts by Weight)			Thickness Inches	Character
	Wax	Plaster	V. Turpentine		
1 to 2	1	1	0	$2\times\frac{1}{4}$	Hardest, frangible
3 to 4	1	1	$\frac{4}{9}$	$2\times\frac{1}{8}$	Hard, but flexible
5	1	1	0	$\frac{1}{4}$	Hardest, frangible
6	1	1	$\frac{2}{9}$	$\frac{1}{4}$	Hard
7 to 8	1	1	$\frac{4}{9}$	$2\times\frac{1}{8}$	Hard, but flexible
9	1	1	$\frac{2}{9}$	$\frac{1}{4}$	Hard
10	1	1	0	$\frac{1}{4}$	Hardest, frangible

Under a uniform load of 1,100 pounds the model was compressed ten times, three stages being shown in *d*, *g*, and *i*.

Results

This model consisted essentially of the massive, competent layer (1) of the preliminary pile, dipping beneath a syncline of deposition and of an overlying competent series of alternating hard and very hard layers. These two competent members acted independently to a certain degree. In the massive layer the initial dip determined the principal anticline of the lower series, which became overturned from the applied force in the stage shown in Fig. *i*.

The absence of dips in the upper series gave immediate effect to the applied force and produced a double anticline near the end. The competent nature of these smaller folds is shown in the axial thickening of the less hard layers. The soft material filling the syncline served to allow independent movements of the two competent members, and was itself deformed by local pressures and relief from load. The overturn in the lower competent member was determined by the fact that one syncline was deeper than the other and the anticline was free to move in the superincumbent soft mass.

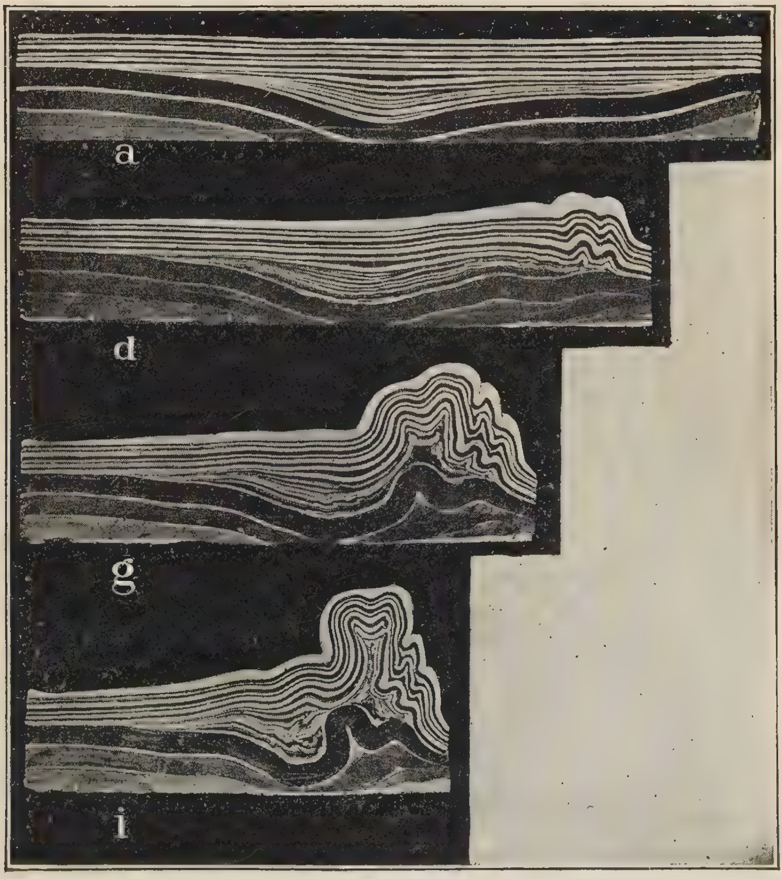


Plate H

PLATE I

Description of Model
Original length, 27 inches.
Width, 5 inches.
Thickness, $3\frac{1}{2}$ inches.

Layers	Composition (Parts by Weight)			Thickness	Character
	Wax	Plaster	V. Turpentine	Inches	
1 to 4 white and black	1	1	1	$4\times\frac{1}{8}$	Soft, but firm and flexible
5 white	1	1	1	$\frac{1}{2}$	
6 to 8 black and white	1	1	2	$3\times\frac{1}{8}$	Softer
9 yellow	1	1	2	$\frac{1}{8}$	
10 and 11 black and white	1	1	2	$2\times\frac{1}{8}$	
12 black	1	1	2	$\frac{1}{4}$	
13 green	1	1	3	$\frac{1}{8}$	Softest This material was like butter at 70° F.
14 black	1	1	3	$\frac{1}{8}$	
15 red	1	1	3	$\frac{1}{8}$	
16 black	1	1	3	$\frac{1}{8}$	
17 and 18 white and black	1	1	3	$\frac{1}{8}$	
19 purple	1	1–	3	$2\times\frac{1}{4}$	
				$\frac{1}{2}$	

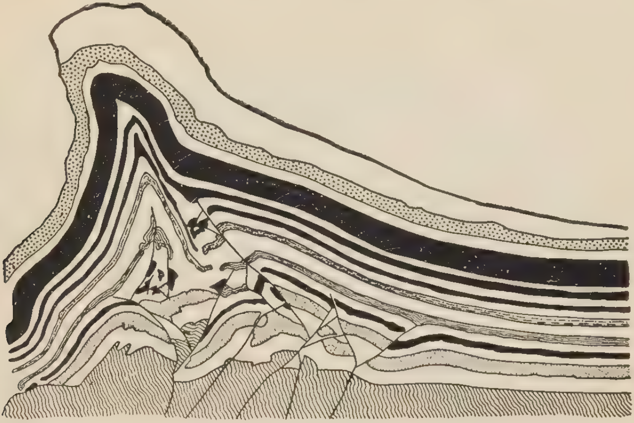
This model was constructed to ascertain the nature of deformation in materials of plastic character confined beneath those of firm and flexible nature. The model was compressed under uniformly distributed load of 1,100 pounds, nine times. The sixth and ninth stages are shown.

Results

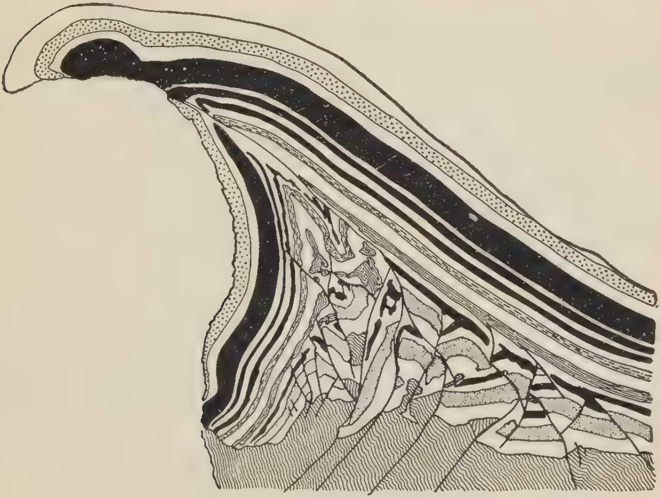
As no initial dips were assumed the position of deformation was determined by swelling near the applied force. In the second stage the arch of the upper strata was entering on development as a competent structure, and the lowest strata were rising into the hollow of the arch by a fault. In this fault the third stage was clearly developed, with clean cut edges, and was confined to the softest, butter-like material, which was relieved of pressure by the overarching competent layers.

As the competent anticline continued to rise the mass of softest material was compelled to change form without change of volume; it was shortened and given space for added height. To this change it accommodated itself by faulting, that is, by flowing on definite planes, not by general flow within the whole mass; the fault-planes divided the mass at first into rhombs, bounded by two faults and two bedding planes, and afterwards into triangular forms, bounded by two faults and one bedding plane. The triangular prisms were so related that the vertical movement in each pair was in opposite directions and the change of form was accomplished as by two wedges moving one against the other. This appears most clearly in Fig. *g*. This faulting may be called incompetent structure in distinction to the growth of the anticline, which is competent structure.

The rise of the competent anticline continued until it overtopped the piston by which pressure was applied. Then the nearer limb of the fold was pushed under the further limb and the strata in the inversion were stretched, producing an overthrust of the alpine type described by Heim—a stretch thrust.



(*g*)



(*k*)

PLATE I

PLATE J

Description of Model

Original length, 24 inches.
Width, 5 inches.
Thickness, 3½ inches.

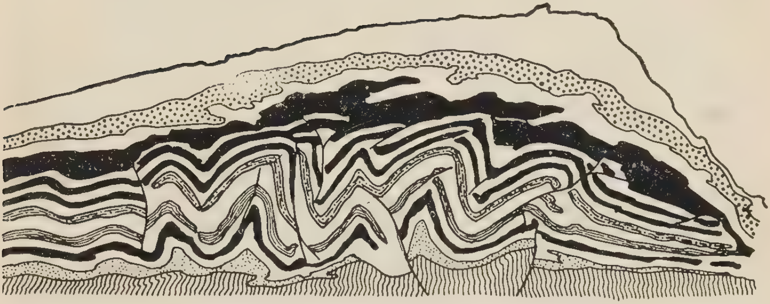
This model was made up of layers which varied in thickness precisely as did those in Plate I; but in this case all the layers were of one consistency, of the softest material that could be handled, composed of wax 1, plaster 1, V. turpentine, 3 parts. This substance resembled butter at 70° F.

The model was compressed under uniformly distributed load of 1,100 pounds, seven times. The figures shown represent opposite sides of the sixth stage.

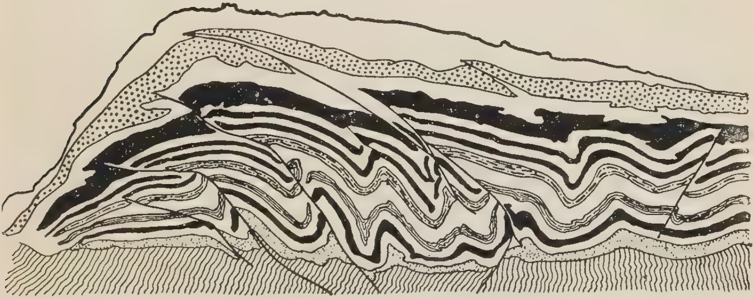
Results

The material being homogeneous and very soft no layer or series of layers, nor even the whole model, was competent to form an arch which would support the load. Therefore the structures developed were incompetent. The first deformation was by shortening and rising near the applied force, and the adjustment of volume to modified form was by rise of the sections on both sides of a wedge-shaped prism. This deformation produced initial dips, which (to an extent limited by the weakness of the strata) caused the resolution of the pressure into components tangential and radial to the curves. The radial components exaggerated the curvature and new initial dips arose, which had a similar effect. Thus folding ensued, but without competent character. There are no carinate anticlines and the strata are not materially thickened or thinned, except in the case of one lower layer; the thickening there indicates a tendency toward competent development of arches of narrow span.

The model was characterized by striking differences of structure on opposite sides; on the one side the dominant feature is folding, with minor faults; on the other side thrusting developed successively from small folds in a manner very much like Cadell's results in hard materials. It is possible that if the substance had been a little firmer only folding would have developed, and if the substance had been softer deformation would have proceeded by thrusting only.



(*g*)



(*g′*)

PLATE J

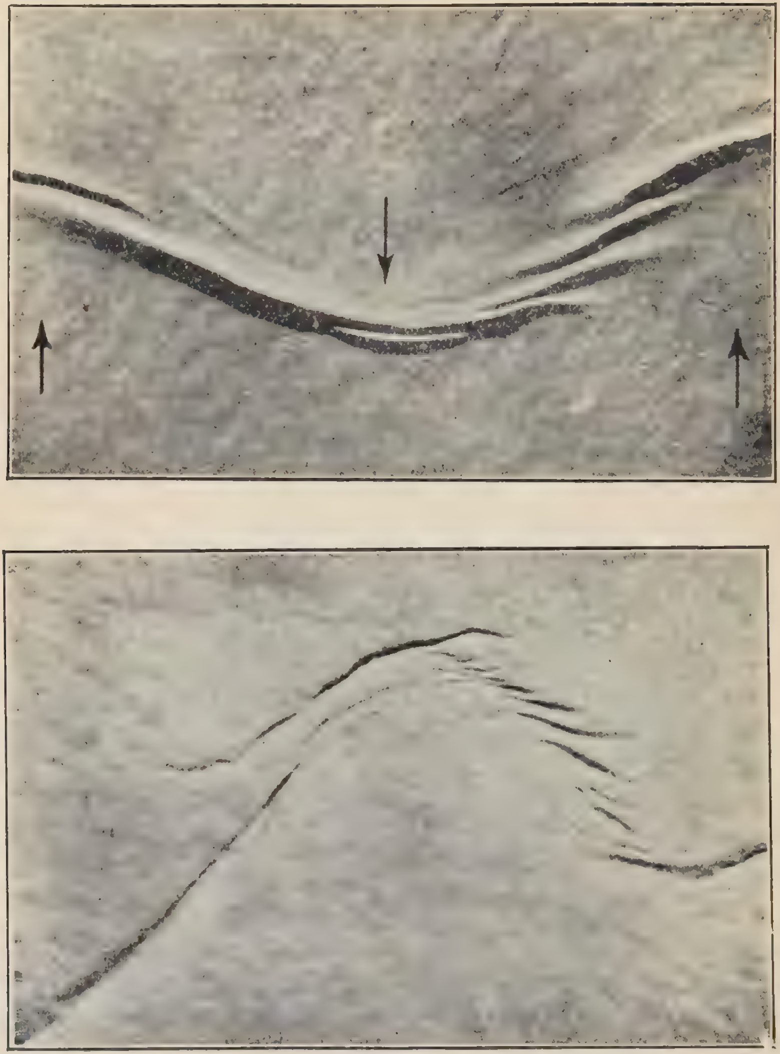


PLATE K

PLATE K

Experiments in echelon folding by S. Tokuda. The experiments were made by mounting rice paper on a layer of soft paste, and exerting pressure on it with the thumb. The folds shown are similar to those formed in arcuate mountain systems. Simple compression is found directly in front of the direction of movement shown by the arrow. On either side of this a shear in a horizontal plane is developed which produces an en echelon arrangement of the folds. Compare the results with Plate K, Appendix III, and with Fig. 116. P275

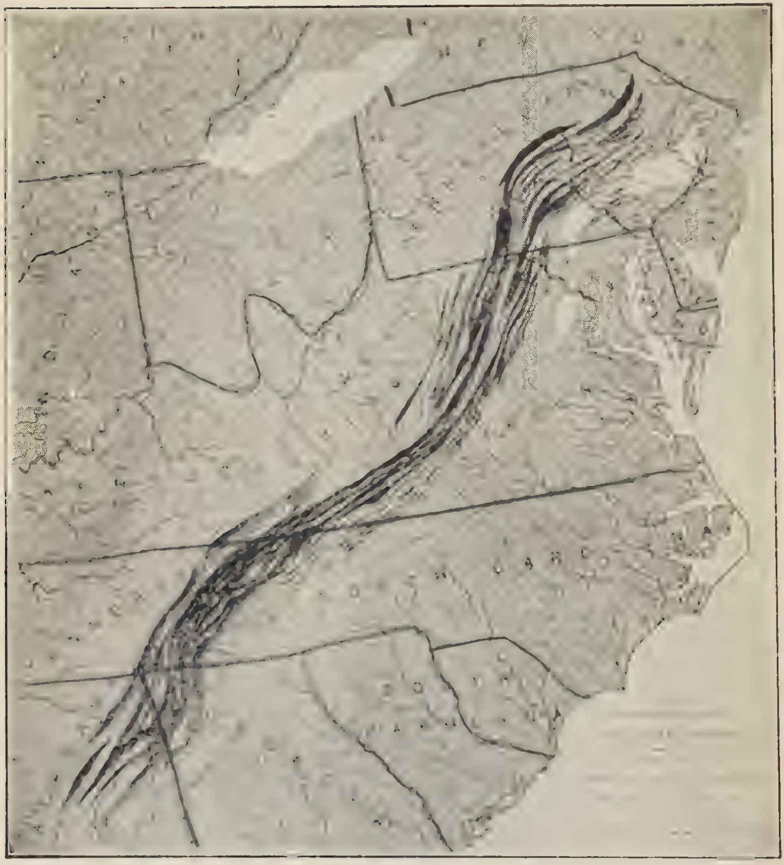


PLATE L

Folded Zone of the Appalachians

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